Evaluation de la performance et aide à la décision pour la Gestion de systèmes industriels : méthodologie basée sur Bénéfice-coût-valeur-risque

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Résumé Étendu en Français

INTRODUCTION GENERALE

Il est nécessaire aujourd'hui de prendre rapidement des décisions fiables à partir d'informations intégrées, dynamiques et relatives de la performance afin de promouvoir une gestion proactive concernant les besoins des clients et du marché. La mesure et la gestion de la performance dans le cadre de l'aide à la décision présentent de sérieux défis pour les ingénieurs et les chercheurs de génie industriel et des sciences de gestion. Cependant, ce problème n'est pas nouveau et beaucoup de méthodologies et d'outils sont déjà proposés dans la littérature. Il est toutefois possible d'apporter des améliorations à celles-ci pour assister les évaluateurs dans la prise de décision d'une manière plus systématique.

Cette thèse propose une nouvelle méthodologie d'évaluation de la performance en suivant quatre dimensions : bénéfice, coût, valeur et risque (BCVR). L'objectif est de développer un cadre complet basé sur les axes BCVR et de proposer une méthodologie opérationnelle et outillée pour la gestion de la performance et l'aide à la décision dans la conception de systèmes ou les projets industriels.

Contexte scientifique

La sophistication et la diversité des produits/services attendus demandés par les clients, les delais courts de la production à la mise en oeuvre d'un produit/service et également les nouveaux concepts (tels que la « servitisation » ou l' « Industrie 4.0 » ont posés d'importants impacts sur l'environnement interne et externe des entreprises et sur leurs systèmes de production. Par conséquent, les entreprises ainsi que d'autres types d'organisations doivent s'adapder aux besoins des clients avec des processus plus flexibles et des ressources mieux coordonnées via les résaux d'entreprise, les chaînes logistiques ou les réseaux de la valeur.

Par ailleurs, les entreprises doivent identifier et satisfaire simultanément les objectifs des différentes partie-prenantes pendant chaque phase du cycle de vie du projet industriel. Les méthodologies de la mesure et de la gestion de la performance sont donc nécessaires pour évaluer efficacement la façon d'atteindre ces objectifs. A cette fin, il est exigé de construire un système facile à utiliser et efficace afin de faciliter la prise de décisions appropriées.

Problèmes de recherche

Les systèmes de la mesure et de la gestion de la performance jouent un rôle important pour évaluer la performance globale d'une entreprise et piloter l'organisation dans leur évolution et leur amélioration continue. Cependant, il y a encore des marges d'amélioration dans ce domaine au vue des méthodes existantes, à cause de :

- l'absence d'une approche intégrée pour la mesure et la gestion de la performance
- la prolifération des critères d'évaluation et la surcharge de données dans la gestion de la performance
- l'insuffisance des liaisons entre la gestion de la performance et des mécanismes d'aide à la décision

Dans ce contexte, le premier problème de recherche de cette thèse est de proposer un cadre méthodologique qui peut inclure toutes les caractéristiques de la performance et simplifier leur présentation. Elle doit être utilisée comme une approche holistique afin de fournir une information intégrée, dynamique et pertinente aux évaluateurs impliqués dans la gestion de la performance.

Le second objectif cherche à développer un moyen opérationnel pour le traitement des données dans l'évaluation de la performance. Il doit comprendre quatre parties principales : *l'analyse descendante* pour identifier les éléments obligatoires pour la mesure de la performance, *la décomposition par les expressions élémentaires* pour les éléments sélectionnés, *l'évaluation par l'opération ascendante* pour obtenir l'expression globale, ainsi qu'une *représentation* pour assister les évaluateurs dans la prise de décision.

Objectifs de recherche

Afin de créer de la valeur pour les différentes parties-prenantes, les entreprises conçoivent et mettent en place des activités pour satisfaire leurs objectifs. Mais la création de la valeur est soumise à des incertitudes et des événements qui influencent négativement les activités de création de valeur. De plus, ces activités consomment des ressources nécessaires au processus de création de valeur. Enfin, ces activités apportent certains avantages potentiels pour les parties-prenantes. Dans ce contexte, la performance d'un système industriel peut être globalement mesurée en suivant les quatre axes : bénéfice, coût, valeur et risque (BCVR).

Un des objectifs de cette thèse est de proposer une méthodologie opérationnelle pour la gestion de la performance et l'aide à la décision basée sur ces quatre dimensions BCVR. Elle peut être le support de : l'évaluation de plusieurs scénarii de décision pour sélectionner la solution la plus appropriée, l'évaluation de la performance au fil des phases d'un projet industriel et le pilotage d'un projet en cours avec plusieurs points d'évaluation durant le cycle de vie.

L'autre objectif est de proposer une méthodologie et ses outils associés, afin d'intégrer les concepts à la fois de l'ingénierie des systèmes et des méthodologies de gestion de projet. Elle peut ainsi aider les évaluateurs à appliquer la méthodologie proposée dans les contextes de projets complexes et de grande ampleur.

Problématique et défis scientifiques

Les principaux défis qui s'appliquent à ce sujet de recherche peuvent être résumés par :

- l'étude detailée des quatre dimensions retenues pour la constitution du référentiel d'évaluation de la performance
- la proposition d'une méthodologie opérationnelle d'aide à la décision
- le développement d'outils appropriés de modélisation et d'évaluation pour appliquer la méthodologie proposée

Structure du mémoire

Comme le montre la Figure 0-1, le mémoire de thèse est organisé et présenté en quatre chapitres

Le premier chapitre présente un état de l'art synthétique étudiant les méthodologies de gestion de projet, les cadres d'ingénierie des systèmes, les systèmes de la mesure et la gestion de la performance dans le contexte d'aide à la décision. Il se focalise aussi sur l'explication des concepts fondamentaux.

Le deuxième chapitre se propose de décrire les travaux réalisés sur les concepts clés et la structure globale de la méthodologie basée sur BCVR.

Le troisième chapitre précise les opérations en détail pour chaque phase (*identification*, *quantification*, *agrégation* et *aide à la décision*) de la méthodologie proposée.

Le quatrième chapitre s'est engagé à illustrer la méthodologie avec trois cas d'étude dans le contexte de la sélection de fournisseurs, l'implémentation de projets de construction et le développement d'un projet informatique.

Enfin, la conclusion présente une synthèse des travaux réalisés. Il discute les résultats et les avantages principaux de la méthodologie proposée. Il propose également les futurs axes de recherche pour améliorer la proposition.

CHAPITRE I : ETAT DE L'ART

Le monde industriel est sujet à différents changements, les décideurs dans la gestion de projets industriels doivent prendre des décisions efficientes et efficaces pour satisfaire les besoins des parties-prenantes impliquées. D'ailleurs, la prise de décision dépend de l'information pertinente en provenance de l'évaluation de la performance. Par conséquent, une analyse de la littérature, des méthodologies et outils actuels pour la mesure et la gestion de la performance dans le cadre de la gestion de projets industriels est réalisé en trois sections (Figure 1-1): les méthodologies de la gestion de projet, les cadres d'ingénierie des systèmes et les systèmes de la mesure et la gestion de la performance.

Parce que ce travail de recherche porte principalement sur le sujet de l'évaluation de la performance et l'aide à la décision pour la gestion de systèmes industriels, les concepts clés et les méthodes essentielles concernant le projet et la gestion de projet, par exemple, les processus de gestion de projets (Figure 1-2), le cycle de vie du projet (Figures 1-5 et 1-6) et les méthods PMBOX et PRINCE2 (Tableau 1-1), sont analysés dans la première section.

D'ailleurs, on peut soutenir qu'un projet industriel peut être considéré comme un système. Les résultats de la mesure et la gestion de la performance pour la prise de décisions doivent être générés sur la base des besoins des parties-prenantes. Par ailleurs, le système industriel ou l'ingénierie d'entreprise est largement tributaire des principes d'ingénierie des systèmes. Dans ce contexte, l'ingénierie des systèmes semble être un cadre efficace pour guider le démarrage pour la gestion de la performance et l'aide à la décision dans beaucoup de projets industriels en particulier pour ceux qui sont grands et complexes. Il est donc important d'examiner les résultats scientifiques dans ce domaine. La deuxième section porte sur les concepts clés d'ingénierie des systèmes (Figure 1-8) et des processus associés (Figure 1-10).

Ensuite, les concepts fondamentaux liés aux systèmes de la mesure et la mesure et la gestion de la performance sont analysés dans la troisième section. En effet, pour tout projet ou problème d'importance pour une entreprise, le management veut savoir quels seront les bénéfices attendus pour l'entreprise, le coût global du projet ou de la résolution du problème, la valeur que cela apportera à l'entreprise et le risque encouru pour l'entreprise. Il est donc considéré que ces quatre axes d'évaluation : le bénéfice, le coût, la valeur et le risque, ont un effet remarquable sur la gestion de la performance et l'aide à la décision dans les projets industriels. Par conséquent, les concepts de bénéfice, coût, valeur et risque sont analysés de façon plus approfondie dans cette section. Les méthodes et outils pour la gestion de la performance et la prise de décision sont également analysés afin d'examiner l'évolution de la méthodologie et de proposer une comparaison entre eux, comme le montre la Figure 1-17.

D'après l'analyse, il y a lieu de conclure que :

- Un projet est divisé en différentes phases au long de son cycle de vie pour faciliter la gestion de projet. Dans chaque phase, les diverses parties-prenantes sont impliquées et les différents processus sont intégrés pour réaliser un controle exhaustif du projet. Dans ce contexte, l'identification des parties-prenantes, l'analyse du cycle de vie du projet et la décomposition par phases constituent les éléments indispensables dans la phase d'initialisation pour la mesure et la gestion de la performance qui est multidimensionnelle et relative.
- Bien que différentes méthodologies de la mesure et la gestion de la performance aient été développées, il est encore nécessaire de proposer une nouvelle méthodologie pour répondre aux caractères de la performance avec un cadre efficace et global. Parce que les dimensions bénéfice, coût, valeur et risque sont les aspects les plus importants dans le cadre d'évaluation d'un projet industriel, il est considère que la nouvelle méthodologie peut-être développée en suivant ces quatre axes.

Etant donné que l'objectif de ce chapitre est de décrire les concepts et les méthodes dans la mesure et la gestion de la performance des projets industriels, le chapitre suivant est consacré à introduire les éléments clés et la structure globale de la méthodologie proposée.

CHAPITRE II : EVALUATION DE LA PERFORMANCE : CONCEPTS CLES ET CADRE

Les pratiques industrielles, soutenues par l'analyse de la littérature, soulignent que la performance globale d'un projet industriel peut être synthétiquement évaluée avec un cadre plus efficace et efficient en suivant les quatre dimensions sélectionnées. Le but de ce chapitre est de présenter les travaux réalisés sur les concepts fondamentaux et la structure globale de la méthodologie proposée.

Comme le montre la Figure 2-1, ce chapitre est structuré en trois sections. D'abord, les analyses conceptuelles concernant les quatre dimensions de la méthodologie proposée sont réalisées pour établir la base de la proposition. Les résultats sont présentés avec les définitions adaptées et les modèles conceptuels. Ensuite, un cadre méthodologique d'expression de la performance, articulé autour de trois perspectives (nommé, les parties-prenantes, les périodes d'évaluation et les variables d'évaluation), est expliqué pour définir une autre base de la méthodologie. A la fin, la structure globale de cette méthodologie d'évaluation de la performance, sur la base des analyses précédentes, est décrite pour montrer les étapes essentielles et leurs interactions. Afin de mieux comprendre ces résultats, un exemple bien connu concernant l'évaluation de la performance d'un projet de thèse a été utilisé pour illustrer à la fois les concepts et les méthodes proposés.

Dans ce chapitre, l'analyse de concepts fondamentaux, par exemple le bénéfice, le coût, la valeur et le risque, est présentée pour définir la base de la méthodologie proposée. D'abord, les définitions nécessaires pour chaque dimension d'évaluation sont adaptées afin de clarifier la signification de chaque dimension. Le bénéfice est définit comme une liste des avantages potentiels pour une partie-prenante procuré par la réalisation du projet ou du système. Le coût est la dépense engagée pour la conception, la fabrication, la distribution et l'acquisition d'un résultat final (un produit ou un service) du projet. La valeur est le dégré de satisfaction d'un besoin ou d'une attente d'une partie-prenante exprimée par le niveau d'appréciation d'un certain nombre d'indicateurs de performance. Le risque est la conséquence de la vraisemblance des événements sur l'atteinte des objectifs des différentes partie-prenantes.

Parmi ces quatre axes, le coût et le risque sont bien connus et étudiés. La notion de valeur a fait dont l'objet d'un soin particulier dans ces travaux. D'ailleurs, les classifications de coûts et de risques (Annexes A et B) ont été proposées comme les listes de référence ou checklist pour les utilisateurs de la méthodologie dans l'identification des coûts ou risques élémentaires par rapport le contexte particulier d'un projet. Puis, les modèles conceptuels (Figures 2-4, 2-5, 2-6 et 2-8) ont été développés sur l'analyse de concepts fondamentaux dans le cadre d'évaluation. Ils ont été alignés pour établir un modèle global qui lie les trois dimensions (coût, valeur et risque) avec une logique commune (décomposition, measure, aggrégation et évaluation). Enfin, basé sur ces relations, un cadre analytique pour l'expression de la performance est proposé afin de décrire d'une manière détaillée et flexible la performance globale d'un système (ou d'un projet) industriel par rapport au contexte particulier de la gestion de performance et la prise de décision (Figures 2-9 et 2-10). Il comprend trois perspectives : les parties-prenantes, les périodes d'évaluation et les variables d'évaluation. En suivant les principes de ce cadre méthodologique, un processus global d'évaluation de la performance avec les quatre dimensions (bénéfice, coût, valeur et risque) est développé pour l'évaluation d'opportunité d'un nouveau projet, la gestion de la performance ou le pilotage d'un projet en cours.

La deuxième partie de ce chapitre porte essentiellement sur la structure globale de la méthodologie proposée. D'abord, plusieurs hypothèses ont été proposées pour définir le contexte d'application de la proposition.

- La méthodologie peut être s'appliquer à un contexte multidimensionnel
- Les quatre dimensions BCVR sont orthogonales au niveau global
- Le coût, la valeur et le risque global(e) d'un projet ou d'un sysème industriel ne peuvent pas être mesurés directement

Après, comme le montre la Figure 2-17, la structure globale de la méthodologie est présentée pour décrire les fonctions principales de quatre phases (identification, quantification, agrégation et aide à la décision) dans le processus d'évaluation de la performance et leurs relations. A la fin, le lien entre la méthodologie proposée et les approches d'ingénierie des systèmes, notamment celui entre le cycle de vie d'un système et le modèle du cycle en V (Figure 2-19), est présenté pour souligner la possibilité et l'avantage d'intégration des méthodes et des outils d'ingénierie des systèmes dans le processus d'évaluation de la performance en termes de spécification des objectifs de parties-prenantes et l'analyse de décomposition.

Le but de ce chapitre est de fournir les concepts de base, la structure globale et les principes théoriques de la méthodologie proposée. Une simple illustration concernant l'analyse de la performance d'un projet de thèse est utilisée en fil rouge pour faciliter la compréhension de la proposition. Cette méthodologie est un ensemble de méthodes et d'outils qui peut guider les décideurs dans l'évaluation de la performance dans le cadre d'atteinte des objectifs. Afin de générer les résultats correspondants, chaque phase de la méthodologie contient différents outils et méthodes qui sont sélectionnés par rapport au contexte particulier de la décision et de la préférence d'évaluation. Les méthodes et outils détaillés ou spécifiques sont présentés dans le chapitre suivant pour compléter la proposition théorique.

CHAPITRE III : EVALUATION DE LA PERFORMANCE : METHODOLOGIE ET PROCESSUS

L’analyse des concepts clés et de la structure globale dans le Chapitre II fournit les principes théoriques au niveau global pour développer la méthodologie proposée. Basé sur ces éléments, les opérations détaillées dans chaque phase (identification, quantification, agrégation et aide à la décision) sont développés pour générer les livrables au niveau élémentaire afin d’implémenter la proposition.

Dans ce chapitre, les travaux de recherche et les résultats sont présentés en quatre sections qui correspondent à chacune des quatre phases principales de la thèse (Figure 3-1). D’ailleurs, l’exemple concernant l’évaluation de la performance d’un projet de thèse est également utilisé en fil rouge dans chaque partie.

Chaque phase utilise certains méthodes et outils pour la mesure et la gestion de la performance. Certains d’entre eux, par exemple l’analyse coût-avantage, la méthode ABC (Activity Based Costing), le tableau de bord prospectif, l'analyse des modes de défaillance, de leurs effets et de leur criticité (AMDEC) et le processus d'analyse hiérarchique, sont déjà largement utilisé pour résoudre des problèmes académiques et industriels. Ils ne sont donc pas discutés en détail dans ce mémoire. Les processus d’opérations de chaque phase sont présentés dans les Figures 3-6, 3-13 et 3-20)

D’après l’analyse de la littérature scientifique concernant la recherche en cours (Tableau 1-2), il y a lieu de conclure qu’aucune des méthodes ou outils existants de la mesure et la gestion de la performance peut répondre au besoin d’évaluation globale et concise de la performance. Plusieurs améliorations peuvent toujours être établies, basées sur le développement actuel. Les apports scientifiques de cette thèse peuvent se résumer en trois points :

- Intégration de différentes méthodes et outils pour développer une méthodologie dans le cadre d’évaluation efficace et efficiente de la performance
- Proposition d’une base commune afin de combiner la mesure de coût, valeur et risque dans le même cadre
- Développement d’un outil de visualisation pour aider les décideurs dans la résolution de leurs problèmes de décision

La méthodologie proposée peut être considéré comme une association d'un semble de méthodes et d'outils qui fournit des orientations pour les évaluateurs dans l'évaluation de la performance d'un système industriel. Cependant, il convient de noter qu'il n'existant pas de combinaison universelle pour touts les types de problème de décision. La sélection des méthodes et outils pour chaque phase de la méthodologie dépend à la fois de la préférence de l'évaluateur et de la disponibilité des ressources nécessaires pour l'évaluation. Les solutions retenues doivent être adaptées au contexte particulier de la gestion de la performance et de la prise de décision.

Dans ce chapitre, le processus d'évaluation en quatre phases et leurs opérations détaillées sont présentés avec une synthèse des méthodes et outils principaux qui peuvent être utilisés dans la pratique. L'objectif de cette section est de fournir un guide pour l'évaluateur dans la sélection des approches adaptées par rapport la situation spécifique qu'il doit gérer en appliquant la méthodologie proposée. D'ailleurs, différents coûts et risques élémentaires dans le cadre de la gestion de projet sont proposés pour aider les évaluateurs à identifier efficacement les variables de coût et de risque concernant un contexte particulier de décision.

Il est considéré que la méthodologie proposée pour l'évaluation de la performance peut être appliquée aux différents types de problèmes de décision dans les divers projets industriels. Outre l'exemple du projet de thèse qui est présenté afin de faciliter la compréhension de la description théorique dans ce chapitre, plusieurs cas d'études dans les autres contextes industriels, par exemple l'évaluation d'opportunité d'un nouveau projet et le pilotage d'un projet en cours, sont présentés dans le chapitre suivant pour appliquer et illustrer la méthodologie proposée.

CHAPITRE IV : EVALUATION DE LA PERFORMANCE : APPLICATIONS EXPERIMENTALES

Les bases et les éléments théoriques de la méthodologie proposée, incluant les concepts clés, le cadre méthodologique et les méthodes et outils associés, sont présentés dans le chapitre précédent. Il est supposé qu'elle peut être appliquée aux situations suivantes :

- L'aide à la décision basée sur l'évaluation du bénéfice, coût, valeur et/ou risque. Il peut être réalisé *à priori* comme l'évaluation des opportunités de différents scénarii afin de sélectionner la solution la plus appropriée dans la phase d'initialisation d'un système industriel. C'est peut être également une analyse *de facto* pour la prise de décision.
- L'évaluation de la performance à toute étape d'un système, processus ou projet industriel (*à priori, de facto* ou *à posteriori*)
- Le pilotage et le controle d'un projet en cours en requérant l'évaluation de la performance dans les différentes phases durant la période du projet.

En prenant en compte la discussion de la fin de Chapitre III, la performance globale des états futures (par exemple une évaluation *à priori*) peut être prévu sur la base de deux éléments : l'expression de la performance globale à un certain période d'évaluation et la variation estimée après l'adaptation.

Afin d'illustrer l'application de la méthodologie proposée dans le cadre de ces types de problèmes, trois cas d'études (la sélection des fournisseurs, l'implémentation des projets de construction et le pilotage d'un projet informatique), en traitant principalement de la prise de décision dans les différents contextes de la gestion de projet, sont développés dans ce chapitre (Figure 4-1).

Les deux premiers cas illustrent l'application de la méthodologie dans l'aide à la décision. Le premier concerne l'analyse sur une seule dimension d'évaluation. Le deuxième inclut toutes les quatre dimensions avec un mélange des variables d'évaluation sous forme d'expressions numériques et linguistiques. Le troisième cas présente l'application de la méthodologie dans le pilotage de projet avec plusieurs évaluations aux différentes périodes d'évaluation du projet.

Cas d'étude 1 : Evaluation des risques dans un processus de sélection de fournisseurs

Le premier cas d'étude traite de l'évaluation des risques dans un processus de sélection de fournisseurs. L'objectif de ce cas consiste à appliquer et vérifier la méthodologie proposée dans un contexte de décision de complexité limitée. Même si l'analyse se concentre sur une seule dimension (risque), les opérations similaires peuvent être appliquées aux autres dimensions.

Comme le montre les Figure 4-2, 4-3, 4-4, 4-5, la décomposition est réalisée en utilisant l'approche de modélisation d'entreprise (IDEF0 et IDEF3). Cependant, il peut être difficile d'identifier un processus standard avec les activités principales qui sont déjà bien définies. Dans ce contexte, la décomposition peut être développée avec d'autres outils, par exemple l'analyse de cause racine ou la modélisation d'objectifs. D'ailleurs, les performances élémentaires dans ce cas sont exprimées qualitativement. Mais, elles peuvent être plus diverses en terme des formes et unités d'expressions.

Afin de réaliser une vérification supplémentaire, un deuxième cas d'étude, traitant de l'évaluation d'opportunité est développé pour compléter l'application de la méthodologie avec toutes les dimensions d'évaluation.

Cas d'étude 2 : Evaluation d'opportunité des projets de construction

Le deuxième cas s'agit de l'application de la méthodologie dans le cadre d'implémentation des projets de construction. Les résultats d'évaluation de la performance sont utilisés pour comparer différents projets afin de décider l'ordre de priorité dans la phase d'implémentation.

Parce qu'il y a moins de données précises permettant d'évaluer la performance, le plus grand défi est de développer l'étape de décomposition afin de démarrer le processus d'évaluation. Basé sur les expériences précédentes dans les projets similaires et d'analyse de causes et effets, la performance globale de chaque projet peut être exprimée par les performances élémentaires avec les structures hiérarchiques (Figures 4-8, 4-9, 4-10).

En conclusion, les premiers deux cas d'études ont illustrés que la méthodologie proposée peut être appliquée aux problèmes de prise de décision avec des activités bien définies ou sans information précise. Afin de vérifier la méthodologie dans une situation plus générique et plus complexe, le troisième cas d'étude est développé pour évaluer la performance dans chaque période d'évaluation d'un projet afin d'adapter le plan d'action et d'assurer le succès de celui-ci.

Cas d'étude 3 : Pilotage d'un projet informatique

Le troisième cas est basé sur un projet réel de développement d'un outil informatique. Comme le montre la section 4.3.2, ce projet a rencontré de nombreux problèmes pendant son exécution. Le but de cette analyse est à posteriori de démontrer l'utilité d'évaluation de la performance pour soutenir les décisions managériales d'un projet industriel.

Le pilotage d'un projet est sujet à plusieurs évaluations de la performance tout au long de son déroulement. Ces résultats fournissent des références à l'évaluateur pour évaluer le coût, la valeur et le risque du projet. Ils peuvent être utilisés pour prendre des décisions concernant les futures améliorations à exécuter.

Dans ce cas d'étude, les mesures de la performance dans chaque période d'évaluation sont générées en suivant les données réelles du projet (Tableaux 4-19, 4-20 et 4-24). L'analyse est développée en suivant quatre « jalons » importants du projet où les évaluations sont nécessaires. Le nombre de mesures est défini par le gestionnaire du projet. Il dépend des points de décision nécessaires dans le projet. S'il y a beaucoup de points de mesures, il serait possible de simuler une trajectoire pour présenter l'évolution de la performance du projet à partir d'un point donné.

D'ailleurs, il est supposé que la structure de décomposition et les critères d'évaluation sont constants dans les différentes périodes d'évaluation afin de limiter la complexité d'analyse. Cependant, dans les projets grands et complexes, les structures hiérarchiques, les critères d'évaluation et la pondération des expressions élémentaires doivent être révisés dans chaque mesure. La même variable d'évaluation peut ainsi être associée aux diverses périodes d'évaluation avec des importances différentes. Afin d'assurer l'exactitude des résultats d'évaluation, les éléments de la performance qui sont générés dans la premier période d'évaluation doitent être adaptés dans chaque mesure de la performance.

Dans ce chapitre, trois cas d'étude ont été développés pour tester la méthodologie proposée dans les différents contextes industriels. Ils ont montrés l'applicabilité pratique de la méthodologie par rapport les divers problèmes de décision. La méthodologie fournit un cadre théorique qui est capable d'évaluer globalement et efficacement la performance d'un système, projet ou processus industriel. Elle est instrumenté avec les outils mathématiques afin d'intégrer à la fois les expressions quantitatives et qualitatives dans les expressions agrégées pour soutenir l'évaluation de la performance. Elle inclut également un moyen de visualisation pour présenter les expressions globales dans le cadre de l'aide à la décision et la gestion visuelle.

CONCLUSIONS ET PERSPECTIVES

En considérant que les objectifs des différentes parties prenantes doivent être satisfaits simultanément dans le cadre de la gestion de projet (ou système) industriel, la performance doit être globalement évaluée. D'une part, dans un environnement hautement concurrentiel, la prise de décision doit être effectuée sur une courte période avec des besoins variés. D'autre part, la plus grande complexité du contexte d'un projet entraîne une prolifération croissante de types de critères à évaluer. Cela augmente la complexité de la collecte et du traitement de l'information. Par conséquent, il est nécessaire de développer une méthodologie plus efficace et efficiente pour aider les évaluateurs dans l'évaluation de la performance et de l'aide à la décision.

La performance d'un projet (ou système) industriel est multidimensionnelle (multi-points de vue, multi-niveaux et multicritères) et relative (dépend de la période d'évaluation et la méthode de mesure). Ces caractères doivent être pris en considération dans l'évaluation de la performance. Autrement, l'expression de la performance n'est ni complète ni exacte.

Après une analyse approfondie de la littérature des méthodes existantes concernant la mesure et la gestion de la performance, ces travaux ont conclu que très peu d'entre elles pouvait répondre à ces exigences. Des améliorations semblent toujours possibles dans le domaine d'évaluation de la performance et d'aide à la décision. Basé sur la thèse précédente de Shah (2012) sur l'évaluation de la performance en utilisant la valeur et le risque, ce travail de thèse a proposé et décrit une méthodologie permettant de mesurer et de gérer globalement la performance en suivant quatre dimensions : bénéfice, coût, valeur et risque.

A propos de l'environnement actuel, il est considéré que la performance d'un système industriel peut-être globalement exprimée et évaluée au moyen de ces quatre dimensions qui régruppées par pairs (bénéfice-coût et valeur-risque, comme le montre la Figure 5-1). Le bénéfice et le coût sont bien étudiés et ils sont souvent analysés ensemble dans la pratique. Même si la valeur et le risque sont largement étudiés, ils peuvent être élaborés d'une façon intégrée pour évaluer la performance. Bien que les quatre dimensions sont orthogonales au niveau global avec des analyses séparées par dimension, ils peuvent interagir au niveau élémentaire en partageant des éléments. Par exemple, le retard du projet est un facteur qui impacte négativement la satisfaction des utilisateurs et les dépenses finales, il influence donc également le coût, la valeur et le risque du projet.

Partant de ces observations, l'objectif principal de cette thèse est de développer une méthodologie qui est adaptée au temps, efficace et facile à utiliser avec une complexité limite pour guider les décideurs dans l'évaluation de la performance et l'aide à la décision. Elle peut s'appliquer à: l'évaluation d'opportunités de plusieurs scénarii de décision, l'évaluation de la performance d'un système/projet/processus dans une période particulière et le pilotage d'un projet/processus en cours des différents contextes de décision.

Afin de développer la méthodologie, ces tâches scientifiques ont été réalisées dans le cadre de la thèse :

- Analyse des concepts clés
- Proposition d'un cadre méthodologique pour l'expression de la performance
- Développement d'une méthodologie d'évaluation de la performance en suivant quatre dimensions : bénéfice, coût, valeur et risque
- Applications expérimentales dans plusieurs contextes de décision

Basé sur ces résultats, on peut conclure que cette méthodologie basée sur bénéfice-coût-valeur-risque peut être appliquée aux diverses situations de décision. Les avantages principaux de cette proposition sont :

- la prise en compte de la multi-dimensionnalité et de la relativité de la performance industrielle
- l'intégration des quatre dimensions d'évaluation dans un seul cadre avec les définitions adaptées et les modèles conceptuels
- la proposition d'une méthodologie qui est adaptée au temps, efficace et facile à utiliser avec la structure globale et les opérations détaillées
- l'applicabilité de la méthodologie dans les différents types de problème de décision
- la flexibilité de la méthodologie selon le contexte particulier et la préférence du décideur

Pour conclure, le cadre basé sur bénéfice-coût-valeur-risque lie les concepts fondamentaux de la mesure et la gestion de la performance. La méthodologie proposée intègre les théories (par exemple, la théorie de la gestion de projet et les théories de la mesure de la performance) et les approches (par exemple, les approches de modélisation et les outils d'aide à la décision) dans un seul cadre méthodologique et elle a été appliquée à l'évaluation de la performance et à l'aide à la décision dans les différents projets industriels à travers trois cas d'étude. La thèse met l'accent sur les contributions scientifiques d'une méthodologie efficace et efficiente dans le cadre de l'évaluation de la performance et de l'aide à la décision.

Concernant les futurs travaux, plusieurs tâches peuvent être développées afin de compléter et d'améliorer la méthodologie proposée.

D'abord, l'application de la méthodologie doit être enrichie dans les autres contextes de décision, par exemple la conception de produits, la planification de procédés et le pilotage de systèmes de production, afin de développer un guide méthodologique. Ces cas, appliqués à des exemples industriels, devraient venir enrichir de façon substantielle la méthodologie.

Ensuite, il s'agit de développer un outil informatique qui permette d'automatiser les opérations proposées dans le processus d'évaluation de la performance. Quand on utilise la méthodologie, il est nécessaire que l'évaluateur ait une bonne connaissance des méthodes et des outils impliqués dans chaque phase afin de sélectionner la combinaison appropriée. Si toutes les opérations sont intégrées dans un seul logiciel, l'application de la méthodologie peut être plus efficace pour les décideurs. Les modèles conceptuels qui sont exprimés par les diagrammes de classes UML dans ce mémoire de thèse peuvent être utilisés comme les éléments de base pour développer cet outil informatique.

En outre, l'amélioration des expressions globales de la performance avec des niveaux tolérables de coût, de valeur et de risque peut être exploitée. La définition des zones de préférence pour chaque dimension d'évaluation serait pratique pour les évaluateurs dans l'évaluation de la performance d'un scénario spécifique de décision. Une méthode plus efficace ou rationnelle peut être proposée pour déterminer ces zones de manière plus systématique dans la présentation visuelle.

Enfin, la variation de la performance serait également intégrée dans la méthodologie afin d'augmenter l'exactitude des expressions globales de la performance en utilisant la méthodologie proposée.

English Version

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GENERAL INTRODUCTION

In today's global competitive markets, decision makers must rely on integrated, dynamic and relevant performance information to ease fast and reliable decision making to promote a pro-active management style regarding customer and market needs. To this end, performance measurement and management for decision support represents serious challenges to practitioners and researchers in industrial engineering and management sciences. Although the problem is not new and that many methodologies and approaches have already been proposed in this field, such as Activity-Based Costing (Cooper & Kaplan, 1988), Balanced Scorecard (Kaplan & Norton, 1992), ECOGRAI (Bitton, 1990), QMPMS (Suwignjo et al., 2000) or the Performance Prism (Neely et al., 2002), just to name a few, there is still room for new advances to go further in assisting managers and engineers to make better decisions in a more systematic manner.

This thesis proposes a new performance evaluation framework built around four main evaluation dimensions: *benefit*, *cost*, *value* and *risk* (BCVR). It extends the thesis of Shah (2012), who worked on value creation and value-risk based performance evaluation of manufacturing processes. Building on advances of this previous doctoral thesis, the aim of the current research work is to develop a complete framework using the four BCVR axes and to propose an operational methodology with recommended associated tools for the sake of performance management and decision support in industrial projects or systems.

This introduction highlights the major points of the scientific context, defines the research problems, outlines the research objectives, presents the main research challenges and introduces the key points of all the chapters composing this report.

Scientific context

Customer demand is now rapidly changing in terms of sophistication and diversity of products and services (Nudurupati et al., 2011). In addition, the time to develop and distribute a product or a service becomes much shorter. Furthermore, new concepts such as "servitisation" (i.e. generating more revenue through integrated product and service offering) or Industry 4.0 (i.e. high connectivity of humans, machines and systems with the production systems but also high connectivity between production systems and their environments by means of Internet of Things) are emerging concepts that will drastically change the management of production systems. These changes will have a great impact on enterprises' internal and external operating environments and these companies are facing tough challenges to succeed in a changing global competitive market. Consequently, enterprises as well as any kind of organisations (business, service or administration) need to become more responsive to customer needs, with more flexible processes and better coordinated resources and partners through corporative networks, supply chains or value networks.

Furthermore, it is common that different stakeholders involved in an industrial process or project have different objectives. To maximise their chance for success, enterprises should identify them and then simultaneously satisfy multiple stakeholder objectives during the different stages of the project life cycles. However, needs, requirements and degrees of satisfaction vary among stakeholders. This problem can even be more complicated because different objectives can be contradictory.

Satisfying objectives requires performance management methods to efficiently evaluate how good the objectives are met. Kaplan and Norton (1992), as well as Ariely (2010), described that "*What you measure is what you get*". Melnyk et al. (2004) indicated that "*You get what you inspect, not what you expect*". These descriptions show that researchers and practitioners have for a long time agreed that "*You can't manage what you can't measure*". Measurement is fundamental to management effectiveness for controlling, reporting, learning and improving. For this purpose, it is necessary to build an easy-to-use and efficient performance measurement and management system to support sound decision making.

Research problems

Performance measurement and management systems play an important role in assessing the overall performance of an enterprise and then guiding the organisation in its evolution or continuous improvement. However, there are still aspects that need to be improved in existing methodologies:

- **The lack of a holistic approach for performance measurement and management**

  The methodologies for performance measurement and management have greatly evolved since the 1960s. The earlier methods mainly focused on cost or financial evaluation, then the later methods integrated financial and non-financial performance measurement and, more recently, new methods turn to integrate performance management systems which take into consideration the multidimensional nature of performance through a wide range of performance indicators. A thorough review and analysis of existing approaches and methods shows that none of them can globally meet all performance characteristics, especially multidimensionality and relativeness (Shah, 2012). The former means that performance relies on multi-viewpoint, multi-level and multi-criteria. The latter means that performance depends on the objectives to meet and it varies over time. It also depends on the way and the conditions under which it is measured and interpreted.

- **Proliferation of evaluation criteria and data overload in performance management**

  Many enterprises are using information technology to capture the required information for informed performance management and decision support. Thus, managers need up-to-date data on each phase of a project or process and on each service of the enterprise to evaluate the business performance of a certain industrial project, process or product. Meanwhile, the fierce competition in the world market and the business evolution increases the number and the diversity of criteria to be considered. Enterprises request ever more performance information to ease fast decision making to face the global competitive market. Therefore, this leads to the proliferation of evaluation criteria and data overload for decision makers. But some criteria measurements are time-consuming while the final results are more or less useful for decision making. In addition, this increases the difficulty of information processing when designing and building performance measurement and management systems.

- **Insufficient links between performance management and decision support mechanisms**

To become more responsive to customer needs, companies are ever more collaborating with one another within supply chains, logistic networks or value chains. But most existing methods of performance measurement and management are rather focused on company viewed as a single, isolated functional entity. Furthermore, the link between performance management and decision support mechanisms is missing in most of the existing methods and approaches.

In this context, the first scientific problem addressed in this thesis is to propose a methodological framework that can embrace all performance characteristics and simplify their presentation. Indeed, excellence in one aspect cannot guarantee a high performance at the global level of a process or project. So, it is necessary to take into account all relevant performance dimensions in performance measurement and management but also to control the complexity of the model when the number of these dimensions grows. The methodology should be used as a holistic approach to provide decision makers with integrated, dynamic and relevant performance information.

The second research problem is to develop an operational way for information processing in performance measurement and management. It should consist of the following main phases: *top-down analysis* to identify relevant elements that are mandatory for performance measurement, *elementary expressions* of the selected elements and *bottom-up computation* to obtain the global performance expression of the elementary measures for performance management. In addition, a *decision support tool* should be also developed to help evaluators in making decisions.

Research objectives

To create value for their stakeholders, companies design and implement activities that will meet their requirements. However, the creation of value is subject to uncertainties and events that might have negative impacts on the activities of value creation. In addition, these activities consume necessary resources during the process of value creation. Hopefully, the realisation of these activities provides some potential advantages for the stakeholders.

Indeed, for all industrial project or process performance management and decision making problems, the management wants to know what will be the expected *benefits* for the organisation, what will be the overall *cost* of the solution to the problem, what will be the added *value* that the project or process will bring to the company and to the other stakeholders and what will be the implied *risks* for the company.

One of the objectives of the thesis is to propose an operational methodology for performance management and decision support based on four assessment dimensions: benefit, cost, value and risk. The aim is to help decision makers to perform opportunity evaluation for a new project/process, to predict future performance of a project/process or to control and monitor execution of an ongoing project/process. It can be applied to various disciplines, such as design, engineering/reengineering, management of production systems for products or services and logistic processes. To this aim, the definitions of cost, value and risk must be revisited.

Furthermore, an industrial process or project, especially large and complex ones, must be considered in the context of an industrial system. Another objective of the thesis is to propose a methodology and associated tools to integrate the systems engineering concepts and project management methodologies.

Scientific challenges

The main scientific challenges addressed by the thesis can be summarised as follows:

- **Completion of a thorough study of the four assessment dimensions in order to construct the performance measurement and management framework**

The concepts of benefit, cost, value and risk are widely used but their definitions are highly variable in different application fields. Even the same term may have several meanings within the same domain. To develop the four dimensions of the framework, it is necessary to define and model each concept as clearly as possible, and it is also important to underline or model their links.

- **Development of an operational methodological framework for decision support**

Generic or global objectives are difficult to be quantitatively measured as they include many dimensions of performance. Therefore, a breakdown analysis must be performed to identify the elements of performance measurement and make them explicit. But this comprehensive evaluation leads to the growing proliferation of various types of indicators. With the high variety of indicators to be considered, building performance measurement and management systems is facing a three-fold difficulty. First, it is necessary to build an efficient system which only provides relevant and reliable information to decision makers. Second, it should be crystal clear how to transform and aggregate the basic measurements into global decision making indicators. Third, the decision support system should be built in a reasonable time and at a reasonable cost. In other words, it must be cost-effective.

- **Development of proper modelling and evaluation tools that can be used to apply the proposed methodology**

One of the deliverables of the thesis is a set of modelling and evaluation tools that allow practitioners to model an industrial project or process, to measure its performance and to present the results in a visual format for decision support.

Thesis structure

The report is structured around four chapters, as illustrated by Figure 0-1.

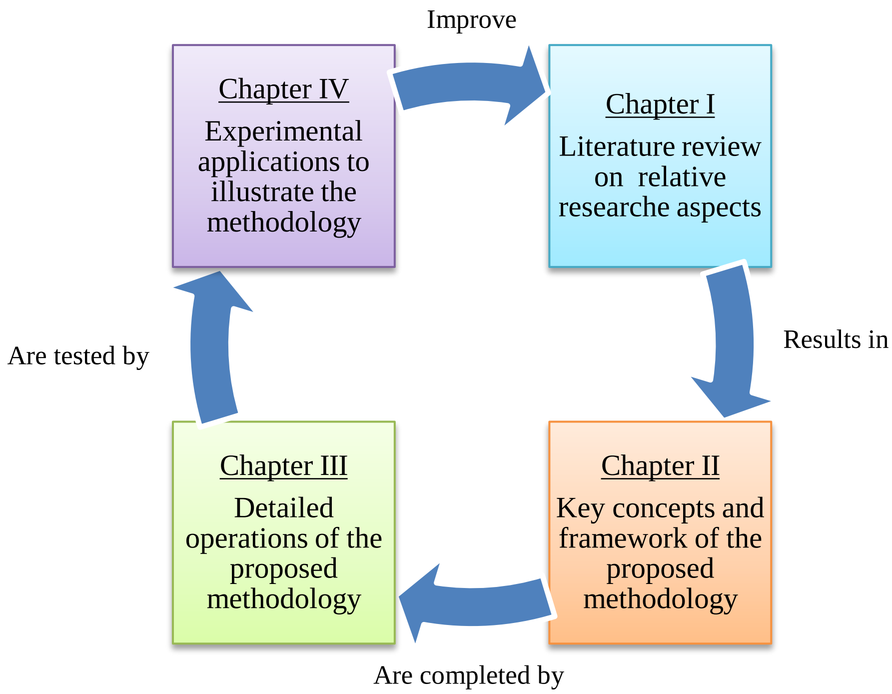


Figure 0-1. Thesis structure

Chapter 1 reviews the existing literature about the main methods regarding the research aspects that are related to project management methodologies, systems engineering frameworks and performance measurement and management systems in the context of decision support. In addition, fundamental concepts, such as project, project life cycle, system, performance, benefit, cost, value and risk as already addressed in the literature, are reviewed and analysed. Furthermore, classical methods for performance measurement and management as well as multi-criteria analysis for decision support are also reviewed. This chapter concludes with a comparison of the reviewed methods to highlight the need to develop a new performance evaluation methodology.

Chapter 2 aims to present the research work that has been carried out on these key concepts and the framework of the BCVR based performance evaluation methodology. Firstly, the proposed definitions and respective conceptual models for the selected BCVR axes are presented to set the basis of the proposition. Then, a performance expression framework based on three perspectives, namely *stakeholders*, *evaluation periods* and *evaluation variables*, is explained to build the fundamental aspect of the proposition. Finally, based on the theoretical bases, the global structure of the proposed methodology is described to show the main steps at the upper level of the methodology and the relations between them.

Chapter 3 specifies the detailed operations of each phase (*identification*, *quantification*, *aggregation* and *decision support*) of the proposed performance evaluation methodology. Each step contains a set of methods and tools to generate the corresponding deliverables at the lower levels for the implementation of the proposed methodology.

Chapter 4 is dedicated to the illustration of the proposed performance management methodology. To explain how the methodology can be applied to different engineering disciplines, three case studies in the context of selection of suppliers, implementation of construction projects and development of an information technology project are selected as comprehensive studies.

The conclusion presents a synthesis of the research work. It discusses the results and main advantages of the proposed operational methodology for performance evaluation and decision support. In addition, it identifies and proposes future research directions to improve this proposition.

CHAPTER I: STATE OF THE ART

In today's global competitive and fast changing environment, decision makers in industrial project management must make effective and efficient decisions to satisfy various requirements from different stakeholders within a limited period of time. However, this cannot be realised without an effective and efficient performance measurement and management system that provides reliable and accurate information for decision support, while evaluating the opportunity of a new project (or system) or monitoring an ongoing project (or system). Therefore, a literature review of existing methodologies and tools for performance measurement and management in the context of industrial project management is discussed in three sections. The structure adopted for the chapter is presented in Figure 1-1.

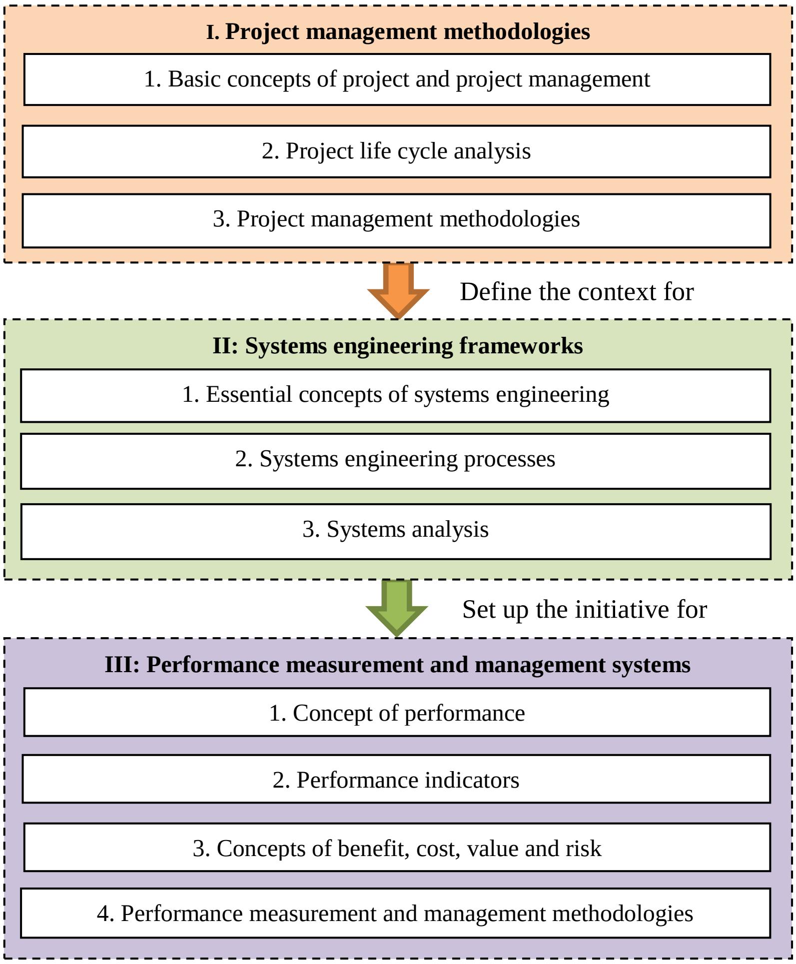


Figure 1-1. Global structure of Chapter I

Because this Ph.D. thesis research mainly focuses on the topic of performance evaluation and decision support in industrial project management, the basic concepts and essential methods concerning project and project management are analysed in the first section.

In addition, it can be argued that an industrial project can be considered as a system. The final information on performance measurement and management for decision making should be generated based on its stakeholder needs or expectations. Furthermore, industrial system or enterprise engineering heavily relies on systems engineering principles. So, in many cases systems engineering seems to be an effective framework to guide the start-up stage for performance management and decision support in industrial engineering projects, especially for large and complex ones. Therefore, it is important to review existing research in this field as well. The second section deals with main concepts of systems engineering and related processes.

After that, basic concepts related to industrial performance measurement and management systems, such as performance and performance indicators, are analysed in the third section. For almost all kinds of industrial projects, the management always focuses on the overall cost of the project, the value created by the project and the potential benefits and risks that are brought by the project. Therefore, it can be considered that these four dimensions, namely benefit, cost, value and risk (BCVR), have remarkable effect on performance management and decision making in industrial projects. Therefore, the concepts of benefit, cost, risk and value are analysed and discussed in more depth in this section. Several prominent methods and tools used for performance management and decision making are analysed to review the evolution of the relevant methodologies and to propose a comparison among them.

1.1 Project management methodologies

Nowadays, the management of companies is facing increasingly complex challenges of different nature such as the need for salary increase while maintaining margins, variable raw material costs, political instability in some world regions, evolving business models, pressure from stakeholders or long-term uncertainty in the industrial sector. These factors are not new, but they were not as acute as the degree they reach nowadays. To face these challenges, several methods and tools are developed and implemented in practice. One of them concerns project management methodologies. The first part of this chapter focuses on major methods for project management.

1.1.1 Basic concepts

To better understand project management methodologies, some basic concepts should firstly be recalled. Therefore, the essential elements of project management based on literature review are summarised in this section.

1.1.1.1 Concept of project

1.1.1.1.1 Definitions

The concept of project has been widely discussed in the literature and has been formalised by various standards associations. A classical definition is offered by Tuman (1983), from whom a project is defined as "*an organisation of people dedicated to a specific purpose or objective. Projects generally involve large, expensive, unique, or high risk undertakings which have to be completed by a certain date, for a certain amount of money, with some expected level of performance. At a minimum, all projects need to have well defined objectives and sufficient resources to carry out all the required tasks.*"

The Project Management Institute (PMI) (PMBOK® Guide, 2013) defines a project as "*a temporary endeavour undertaken to create a unique product, service or result"*. Similarly, another definition describes a project as "*a unique process, consisting of a set of coordinated and controlled activities with start and finish dates, undertaken to achieve an objective conforming to specific requirements, including the constraints of time, cost and resources*" (ISO/FDIS 9000, 2015).

Based on these definitions, it can be concluded that a project is identified by three elements which are: (1) a specific objective (purpose) to create a unique outcome (a product, service or result), (2) a unique process with a set of activities and (3) several particular constraints including expected delivery time, expenditure and quality. Therefore, the performance evaluation of an industrial project should include these aspects.

1.1.1.1.2 Characteristics

Prabhakar (2008) argued that most projects share five typical characteristics: (1) a start and a finish; (2) a time frame for completion; (3) an involvement of several people on an ad-hoc basis; (4) a limited set of resources and (5) a sequencing of activities and phases.

Based on the definitions of project, it can be concluded that a project is bounded in time and unique. The bounded nature indicates that a project has a finite time-scale for completion defined by beginning and end points. During this period, the project consumes necessary human, material and financial resources. At the end of the time-scale, a project may be completed successfully with the achievement of its stated objective, or it has failed because the expectations of the client have not been or cannot be met. A project can also be terminated before the end of its time-scale if the client wishes to stop it.

The uniqueness characteristic conveys the fact that a project creates a particular outcome that may be tangible (for examples, materials, components or pieces of equipment) or intangible (for examples, data, information or knowledge). A project can create a new product or service, a change in the operation of an organisation, a document that can be used to make a decision or an improvement in the existing business processes and procedures. In some cases, the outcome of the project may contain repetitive elements, but it does not change the nature of the project. The product, service or result that is created by the project is still unique. Therefore, there may be uncertainties or differences in the outcomes that the project creates. However, some common elements can be identified among different projects. They can be applied to performance evaluation in the context of new project development.

1.1.1.1.3 Project versus process

The concept of project is often mixed up with the concept of process. So, it is necessary to distinguish these two concepts.

A process is defined as "*a set of interrelated or interacting activities that use inputs to deliver a pre-specified product, service, or result*" (ISO/FDIS 9000, 2015). These activities have an organised and repetitive sequence. Similarly, Vernadat (2007) defined that "*a business process is a partially ordered sequence of steps executed to perform some enterprise goals. It represents a full chain of processing, from its starting point to its finish characterized by the delivery of its end-result(s) as expected by the process owner*". According to these definitions, it can be considered that a process is repetitive. This nature shows that a process is a set of actions that can be easily duplicated or iterated while a project is a unique sequence of tasks. It can also be considered that a project focuses on the final outcome while a process is about how to generate the expected result.

Although a project and a process are different, these two terms may be sometimes interrelated. They share some common attributes, for instance, both of them are performed by people with constraints of limited resources. A project or process can involve either one single participant or multiple participants. These participants can be individuals or organisational units. In addition, the generic phases in a project or process life cycle can be summarised as: planning, execution, control and monitoring.

To conclude, a project can be defined as a process that is executed only once. For instance, preparing a doctoral thesis is a project for the student but it is a process that can be run several times for the research laboratory hosting the student (the Ph.D. example will be used as an illustrative case study in the following chapters of this document).

1.1.1.1.4 Classification

According to Prabhakar (2008), projects can be categorised regarding the following elements: (1) project size, (2) project complexity, (3) external or internal customer, (4) degree of customer involvement in the project and (5) levels of risk.

Project size can be measured by several dimensions, for example, the amount of resources involved (money, skilled people or facilities), scope and geography. Large scale in any of these dimensions usually results in higher risk.

Project complexity is decided by the diversity in the project objectives and scope, number of different internal and external stakeholders involved and the sources of technology and funding. Joint venture form and interaction of projects with ongoing operations are common sources of complexity.

Different management challenges are posed by external and internal customers. The contractual terms will directly affect the degree of risk associated with a project. For example, the legal constraints may not be applied on a project for an internal customer. This may lead to the errors in specification in project planning and control. As a result, it may increase the risk that the final output of the project will not meet its desired objectives.

In many projects, the customer must itself perform a significant contribution to ensure that the project can be accomplished on schedule and meet the predefined requirements. Customer tardiness will cause delay and additional cost on the project. Besides, the risk involved in projects vary among different types of projects based on the following elements such as the degree of innovation, project size, duration, urgency, complexity, contractual terms and availability of resources.

Understanding the characteristics of a project in the above categories can help the evaluators to predict problems and put measures in place to avoid them. In addition, the project management tools and organisational change are closely related to the specific type of project.

1.1.1.2 Project management

It should be noticed that project success depends on different elements. For example, clear and precise definition of needs, accurate evaluation of required resources and competencies, knowledge of project management team, implementation of preventive and corrective actions, clearly formalised responsibilities and priorities within the project team, availability of resources and support, implication of stakeholders, efficient and adapted communication and efficient management, planning and follow-up, can be mentioned. To ensure the success of a project, project management is needed to guide the project management team to better perform these elements throughout the project.

Diallo and Thuillier (2004) outlined a set of evaluation dimensions, which appear regularly in the project management literature. These are: (1) respect of the three traditional constraints: cost, quality and time; (2) satisfaction of the client; (3) satisfaction of the objectives outlined in the logical framework; (4) project impacts; (5) organisational capacity built in the organisation by the project; (6) financial return or the economic or social benefits and (7) project innovative features (outputs, management and design).

Project management is a specialised branch of management, the aim of which is to co-ordinate and control some complex activities of modern industry (Prabhakar, 2008). It is a central strategy for many organisations to build a more dynamic model in face with today's changing business environment. Regarding the final purpose of a project, Lock (2013) indicated that a large industrial project involves numerous differentiated activities, from the beginning of the work to the delivery of the final output, with a focus on one final target. The aim of project management is to finish the project on time, within budget and delight the project investor and all the other stakeholders. More specifically, Kerzner (2009) defined project management as "*the planning, organizing, directing, and controlling of company resources for a relatively short-term objective that has been established to complete specific goals and objectives.*"

According to the Project Management Institute (PMBOK® Guide, 2013), project management is "*the application of knowledge, skills, tools and techniques to project activities to meet project requirements*". Managing a project typically includes: identifying requirements, addressing stakeholder needs and expectations in planning and executing stages, managing stakeholders and balancing project constraints (for example, scope, quality, budget, resources). It is accomplished through the appropriate application and integration of numerous project management processes within five process groups: initiating, planning, executing, monitoring & controlling and closing (Figure 1-2).

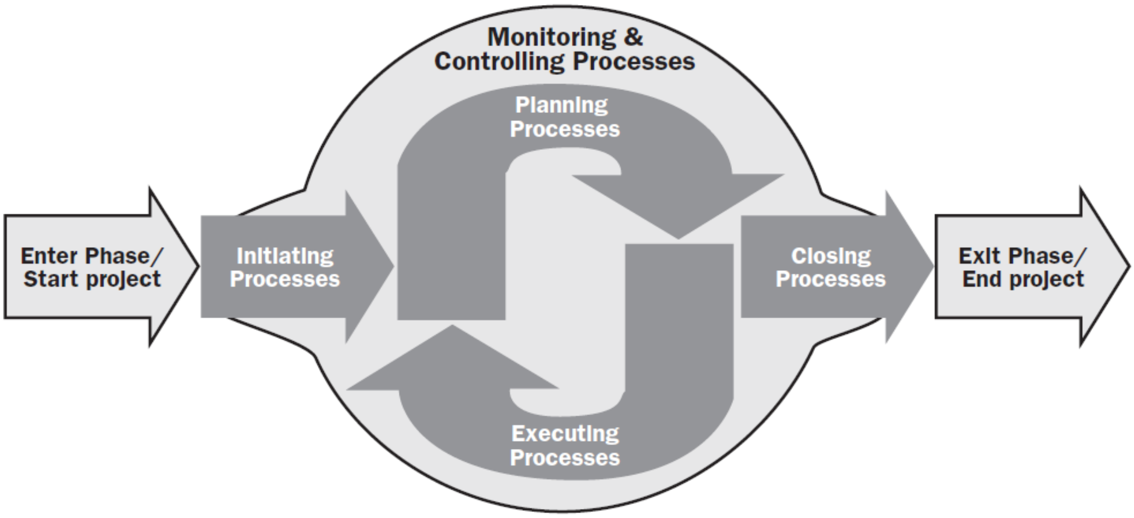


Figure 1-2. Project management process groups (PMI, PMBOK® Guide, 2013)

Initiating processes are performed to define and organise a new project or a new phase of an ongoing project by obtaining authorisation to start the project or phase. Planning processes are required to establish the detailed scope of the project, refine the objectives and define the course of actions to attain the objectives. Executing processes are performed to complete the work defined in the project management plan to satisfy the specification. Monitoring & controlling processes are required to track, review and regulate the process and performance of the project, identify any necessary changes to the project management plan and initiate the corresponding changes. Closing processes are performed to finalise all activities across all process groups to formally close the project or phase. These processes ensure the effective flow of a project throughout its life history and they are performed by the project team with consideration of project stakeholder requirements.

These project management processes are interactive, because change in one process will affect this process itself and other related processes. For example, the adjustment in project budget in the planning process will change the project delay and level of risk in the executing and monitoring processes. Therefore, these interactions often require specific performance trade-offs among project requirements and objectives from different stakeholders. Depending on the decision maker preferences, these trade-offs vary from projects as well as organisations.

In this context, project management is an integrative practice that requires each project and product process to be appropriately applied and connected to facilitate the organisation and coordination among them. Successful project management relies on successful management of these interactions to meet simultaneously different stakeholder requirements. In some cases, one project management process or several processes should be iterated in order to achieve the specific project requirements.

For better understanding of stakeholder requirements, the project management team should identify the roles of all involved stakeholders and relationship among them. Then, their objectives should be identified and modelled for the purpose of project performance evaluation. Therefore, the concepts of stakeholder and objective, as essential terms in different project management methodologies, are presented in the following sections.

1.1.1.3 Stakeholders

Several individuals and organisations are actively involved as project stakeholders in different phases along a project life history. According to the Project Management Institute, "*Project stakeholders include all members of the project team as well as all interested entities that are internal or external to the organisation*" (PMBOK® Guide, 2013). Their interests may positively or negatively influence the project and its result. Although the final result of a project is influenced by different elements, the implication of stakeholders is critical to the success of the project.

Based on different characteristics, project stakeholders can be divided into different categories, such as internal and external, positive and negative, performing and advising. They should be clearly identified in order to determine the project requirements and the expectations of all parties involved to ensure a successful outcome.

In addition, stakeholders have different levels of responsibility and authority in an industrial project. Some may only have occasional contributions in surveys, but others may have full project sponsorship in terms of financial, political or other support.

The project team should identify the list of stakeholders, understand their relative importance and degree of influence on the project and balance their demands. Failure to do so would result in additional cost, unexpected delay and other negative impacts (such as decrease of the project value). For example, late recognition that the doctoral school is a significant stakeholder in a doctoral research project could lead to delays due to failure to fulfil administrative requirements at the time of thesis defence. Typical stakeholders of a Ph.D. project are: the student, the supervisors, the doctoral school and the academic institutions hosting the student.

1.1.1.4 Objectives

Project success should be measured in terms of completing the project within satisfaction of several predefined conditions such as the constraints of scope, time, cost, quality, resources and risk. Therefore, the result of measurements is more or less translated into ratios, being implicitly referred to a target point which is called *objective* (Berrah & Foulloy, 2013). A similar definition describes an objective as "*the goal that an organisation intends or sets to meet during a specified period*" (Mauchand, 2007). Keeney (1994) specified an objective as "*a statement of something that one wants to strive toward*". In addition, an objective is characterised by three features: a decision context, an object and a direction of preference.

In this case, it can be concluded that an objective is a statement of desired outcome which is expected by an individual or organisation during a specified time-scale. It can be described as a trend, an optimised expression or more precisely as a specified numerical value. For instance, reducing manufacturing costs by 15% over the next 6 months, minimising the risk of choosing a subcontracting method or decreasing a delivery time by 10% before the end of the year are examples of objectives (they must have a time limit for their achievement).

Based on these definitions, objective achievement should be the driving force in decision making processes. The critical question then becomes "How to define meaningful objectives to be achieved?" Doran (1981) proposed the SMART method for setting objectives. An objective must be "*Specific (target a specific area for improvement), Measurable (quantify or at least suggest an indicator of progress), Assignable (specify who will do it), Realistic (state what results can realistically be achieved, given available resources) and Time-related (specify when the result(s) can be achieved)*". However, it should be noticed that these criteria do not mean that all objectives must be quantified at all levels of management. Serious management should focus on the combination of objectives and related action plan. Besides, the acronym "SMART" does not mean that each objective will have all the five criteria. It is a baseline to help individuals and organisations to set effective objectives.

Over the years, other explanations or additional terms have been introduced around this SMART acronym. In some cases, A is explained as Achievable (set the objectives at the right level) and then R is for Relevant (ensure that each objective is relevant to the role of its owner and different objectives are supporting each other). In addition, two criteria "Evaluated (appraisal of a goal to assess the extent to which it has been achieved) and Reviewed (reflection and adjustment of the approach or behaviour to reach a goal)" are added to propose the SMARTER method (Yemm, 2012).

Objective setting is also applied as the basis for the identification of better decision alternatives. In this context, Keeney (1992) developed a method which is called "Value-Focused Thinking (VFT)" to take better decisions. Unlike traditional decision making methods that focus on evaluation of alternatives, the aim of the VFT method is to generate the best decision alternative based on clear and structured objectives modelling.

This method distinguishes two types of objectives: *fundamental objectives* and *means objectives*. Fundamental objectives reflect the ends that the decision makers want to achieve in a specific decision context. They are described as "*a statement of something that one wants to strive toward*" (Keeney, 1994). The fundamental objectives can be further divided into "*strategic objectives*" that provide common guidance for all decisions in an organisation and "*more detailed fundamental objectives*" that are appropriate for specific decisions. Meanwhile, means objectives are defined as "*methods to achieve fundamental objectives*" (Keeney, 1994). They provide links from the conceptual top-level organisational objective to the measurable detailed alternatives.

In the context of performance management and decision support in industrial projects or processes, objectives modelling should be integrated with process modelling methodologies to generate an overall solution. From the point of view of process modelling, a project or process can be considered as a set of activities that realise corresponding functions. Meanwhile, the VFT method provides the objectives at different levels which can be associated with process steps in the process modelling structure.

To this end, several models are proposed to link industrial process modelling and objective modelling. At the activity level, Vernadat et al. (2013) proposed an activity-based model in a performance perspective (Figure 1-4).

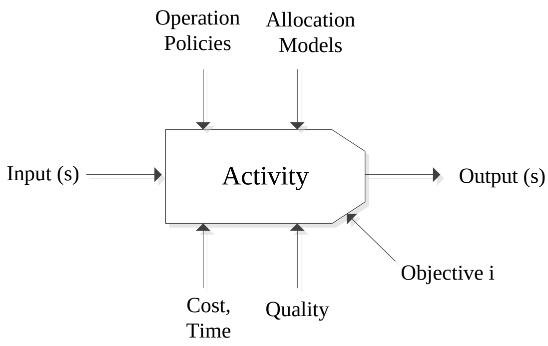


Figure 1-3. Activity model in performance perspective (Vernadat et al., 2013)

This model is based on the IDEF0 formulation of an activity. Certain attributes are intrinsic to an activity, such as cost, time and quality, in the context of performance assessment. Activity performance is measured with reference to the associated objectives which are considered as the means objectives in the VFT method.

At the process level, Neiger et al. (2009) proposed the Value-Focused Process Engineering (VFPE) methodology that combines extended Event-driven Process Chain (e-EPC) process modelling methodology (Scheer & Nüttgens, 2000) and the VFT objective modelling methodology. In an event-driven process, different events describe under what circumstances a function (a task or activity) works or results in. In the VFPE methodology, it is considered that there exists the synergetic interrelationship between the e-EPC and VFT components. The business objectives at each level correspond to the relevant function, as shown in Figure 1-4. This association between activity modelling and objective modelling can be applied to breakdown analysis based on the results of enterprise modelling in certain decision situations.

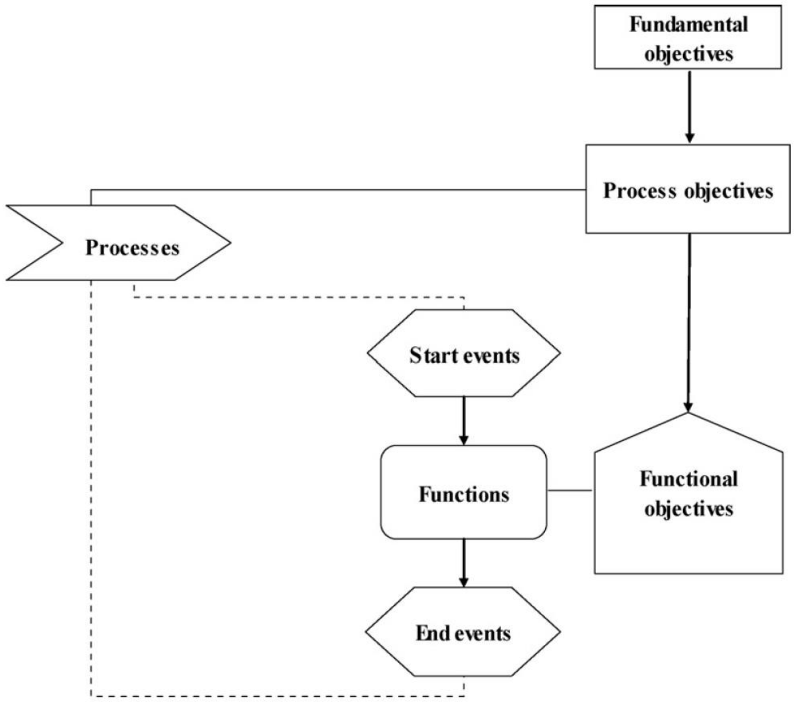


Figure 1-4. Overview of VFPE methodology (Neiger et al., 2009)

While managing a project or process, the objective modelling can help evaluators to conduct performance evaluation from the upper level to the lower level to ensure the accomplishment of stakeholder objectives.

1.1.2 Project life cycle and project phases

Project success mainly depends on whether the stakeholder objectives are satisfied. However, the satisfaction should also be realised within a predefined duration. Therefore, project life cycle and project phases are always applied as important terms in project management.

1.1.2.1 Project phases

To efficiently manage and follow-up a project, a project is divided into different phases along its life history (i.e. over the time axis). Lockyer and Gordon (1996) indicated that, in general, all projects pass through at least four identifiable phases: design, development, execution and closing. According to Archibald and Voropaev (2003), generic project phases can be summarised as: concept (initiation, identification and selection), definition (feasibility, development, demonstration, design & prototyping and quantification), execution (implementation, realisation, production and deployment, construct, installation and test) and closeout (termination, including post-completion evaluation).

Each project phase is marked by the completion of one or more tangible deliverables, which are usually approved before work starts on the next phases. There may be different relationships (for example, overlapping, sequential and parallel) between individual phases. The applied relationships are determined by elements such as level of control required, effectiveness and degree of uncertainty.

1.1.2.2 Project life cycle

The Office of Government Commerce (PRINCE2, 2009) describes a project life cycle as *"The period from the start-up of a project to the acceptance of the project product.*" The Project Management Institute (PMI) defines a project life cycle as "*the series of sequential phases that a project passes through from its initiation to its closure*" (PMBOK® Guide, 2013). The number of generic phases in a project life cycle depends on numerous factors such as the nature of the industry project output or the project size (Prabhakar, 2008) and they are determined by the management and control needs of the company and stakeholders involved in the project. A theoretical sequence of generic phases that may be applied to most of the projects can be: conceptualisation, planning, testing, implementation or execution and closure (Kerzner, 2009).

Although projects vary in different elements (as mentioned in the section on classification of projects), almost all projects can be mapped to a generic life cycle structure: (1) starting the project, (2) organising and preparing, (3) carrying out the project work and (4) closing the project. In addition, it can also be applied to one project phase, a specific task in a project or a product life cycle. Along different project life cycles, the flowing characteristics can be summarised.

- Cost and staffing levels are low at the start and reach a peak as the project is carried out (Figure 1-5). For instance, more than 90% of a product final cost (Arc 1) depends on the choice made in the design phase (including pre-study and study steps) of a product development project. This incurred cost is regularly compared with the real expenditure (Arc 2), which is less than 15% of the cumulative actual spending. It can be argued that the decisions in the design phase have strong impact on the final product cost.

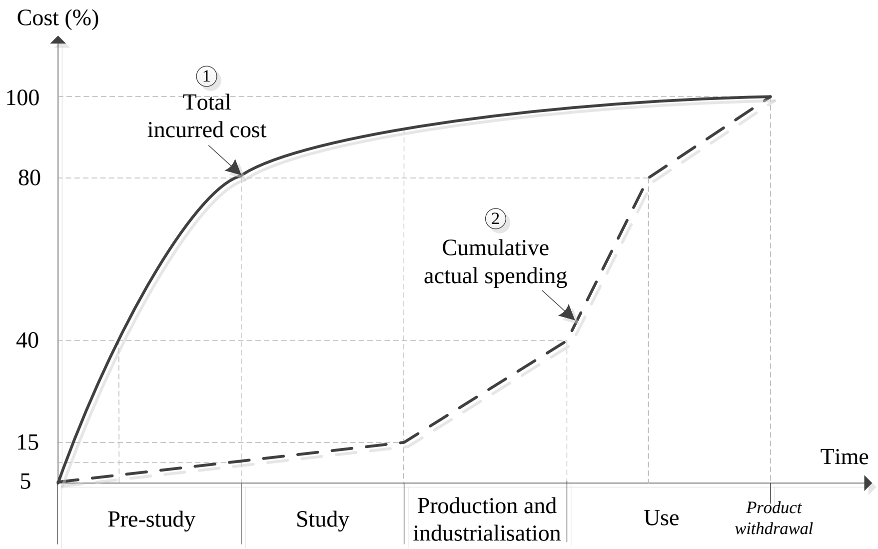


Figure 1-5. Incurred cost and actual spending during product life cycle (Bourdichon, 1994)

This observation can be also applied to in the context of project management. However, this curve may not apply to all types of projects. In some cases, significant expenditures may be required in the early stage of project life cycle to secure necessary resources. In addition, the cost of making changes and correcting errors increases substantially as the project goes along.

- As shown in Figure 1-6, risk and uncertainty are at the highest at the beginning stages of a project (Arc 1). These factors begin to reduce as the project continues until the decisions are reached and project deliverables are accepted. Meanwhile, value is cumulated along the product or project life history (Arc 2). It reaches the highest level at the end stage with the delivered final outcomes.

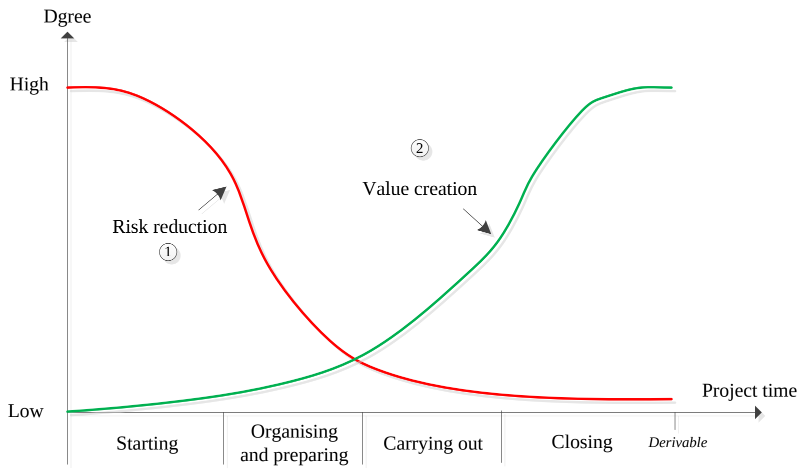


Figure 1-6. Risk reduction and value creation along project life cycles

- The ability of the stakeholders to influence the final characteristics of the project result is the highest at the start and gets progressively lower as the project progresses towards completion.

Within the context of project life cycle structure, the project team can determine the need for more effective control, particularly in large and complex projects. Based on the descriptions of Archibald and Voropaev (2003), the objectives of defining the project life cycle for each project are to better understand the process to be followed along a project life history, to record the best experience in order to continually improve the project life cycle process and duplicate it on other projects and to appropriately integrate different project management methods and tools with the overall project life cycle management process. It can be summarised that the life cycle provides the basic framework for managing the project, so identification of common life cycle processes is an important starting point in project management.

All projects consist of different phases which form the project life cycle. Each phase is often planned, scheduled and managed as a separate project from start to finish of each phase. However, this usually results in conflicts while being swept forward into the next phase (Archibald et al., 2012). For example, the costs of operating and maintaining a product line are often increased because the designers took short-cuts to reduce the design costs and increase their profits. Therefore, an overlapping of different phases should be taken into consideration to resolve the conflicts as early as possible in the entire project life cycle through different project management methodologies.

1.1.3 Project management methodologies

Projects are successful if they are accomplished on time, within budget and if they meet stakeholder requirements. Achieving this goal is more likely within the context of a repetitive process, while it should also apply in the context of a project management methodology to be used for a specific project (Kerzner, 2009). Each project methodology contains project phases, measures progress, takes corrective actions based on defects found and assigns resources to various phases (Charvat, 2003).

The basis for the development of project methodologies is project management standards. Three main project management standards, namely ISO 21500 standard (ISO 21500, 2012), the Project Management Body of Knowledge (PMBOK® Guide, 2013) by the Project Management Institute (PMI), USA and PRojects IN Controlled Environments (PRINCE2, 2009) by APMG, UK, are considered the base in today's research and practice.

The Project Management Institute divides project management into ten knowledge areas: integration, scope, time, cost, quality, human resource, communication, risk, procurement and stakeholder management. A knowledge area represents a complete set of concepts, terms and activities that make up a professional field, project management field or area of specialisation.

ISO 21500 follows the ten knowledge areas defined in the former versions of PMBOK and just renames them to subjects. Therefore, it is considered that these two standards are quite similar and complement each other.

The PRINCE2 (2009) process model comprises seven distinctive management processes throughout a project life. These are: starting up a project (SU), directing a project (DP), initiating a project (IP), managing a stage boundary (SB), controlling a stage (CS), managing product delivery (MP) and closing a project (CP), as shown in Figure 1-7.

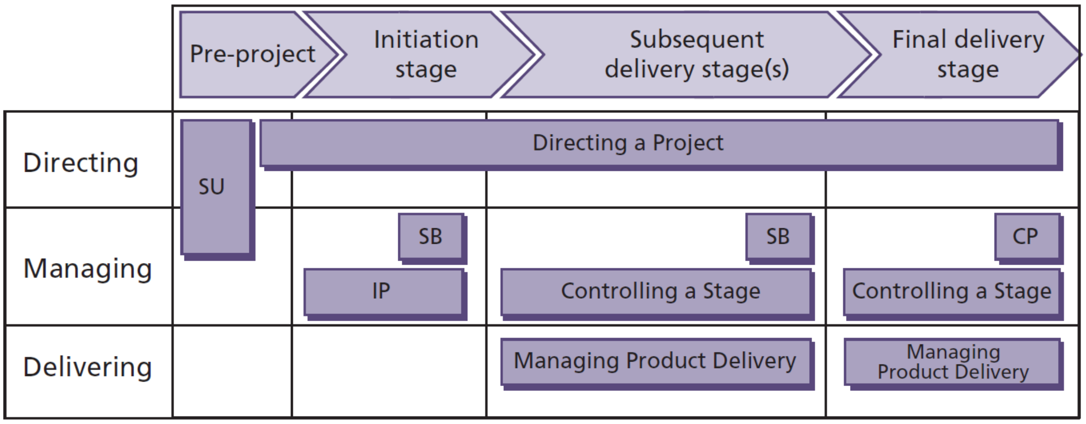


Figure 1-7. PRINCE2 processes (PRINCE2, 2009)

Based on the principles of PMBOK and PRINCE2, Singh and Lano (2014) made a comparison of these two standards, as shown in Table 1-1.

Table 1-1. Comparison of PMBOK and PRINCE2 (Singh and Lano, 2014)

PMBOK	PRINCE2
Comprehensive	• Focuses on key areas • Does not claim to be complete
Largely descriptive, prescriptive on a high level	Highly prescriptive, especially on process structure, but adaptable to any project size
• Core and facilitating processes • Need to be scaled to the needs of the project	• All processes should be considered • Need to be scaled
Customer requirements driven	Business case driven
Sponsor and stakeholders	Clear project ownership and direction by senior management
International/UK standard	UK standard

Considering the project management standards as the baseline, a large number of techniques are developed to bring different components (for example, planning and scheduling, developing and monitoring progress) of large and complex projects into control.

If possible, companies should maintain and support a single methodology for project management, and a good methodology should integrate other processes for improvement. Kerzner (2009) concluded that the processes of project management, total quality management, concurrent engineering, scope change control and risk management were integrated during the 1990s. Since 2000, supply chain management processes, business processes, feasibility studies, cost-benefit analyses and capital budgeting have been integrated.

In summary, choosing an appropriate project management methodology is like choosing which recipe to follow while cooking a certain dish. Although different recipes do not use the same ingredients and techniques, each of them provides delicious results at the end. So, the project management methods and tools should be selected based on the particular context such as project constraints, time schedule and people.

In this section, the key concepts of project management, such as project, process, stakeholder and objective, have been presented to elaborate the context for this Ph.D. research. Project success relies on satisfaction of predefined stakeholder needs within a limited duration. Therefore, project management should be developed on temporal units which are described as project life cycles or phases.

Along the project time, the overall cost, value and risk, as well as the influence of stakeholders, evolve and must be evaluated. Because decisions that are made in the initialising stage have strong influence on the incurred cost and risk reduction, the starting phase should be emphasised in project management. Along the whole life history or in a specific life cycle phase, different project management processes are applied to guide the project manager. Based on these processes, three main standards and methods have been compared to summarise project management methodologies.

In addition, to develop the analysis of project life cycle phases and expression of stakeholder needs in industrial systems, the systems engineering framework can be considered as an effective approach. Thus, the following section focuses on the literature review of systems engineering.

1.2 Systems engineering frameworks

To face the design or management of a large and complex industrial system, the creation of an abstract system can help in explaining complex situations in the real word. Also, it should be kept in mind that this thesis work is mostly dedicated to industrial systems, such as goods or service production systems. Thus, a systemic approach can be applied to fully explore problems and solutions in the identification of stakeholder requirements. For this purpose, the key concepts and relevant processes used in systems engineering are reviewed in this section. Indeed, from a methodological point of view, systems engineering ensures that all likely aspects of a project or system are considered and integrated into a whole.

1.2.1 Key concepts

1.2.1.1 System

The concept of system is widely used in many areas. ISO or IEEE standards propose definitions of the system concept in the field of systems engineering (SE). For instance, among these we can cite, "*an interdependent group of people, objects, and procedures constituted to achieve defined objectives or some operational role by performing specified functions*" (IEEE standard 1233, 1998); "*a collection of interacting components organized to accomplish a specific function or set of functions within a specific environment*" (IEEE standard 1362, 1998); "*a set or arrangement of elements that are related, and whose behaviour satisfies operational needs and provides for the life cycle sustainment of the products*" (IEEE standard 1220, 2005); "*an interacting combination of elements to accomplish a defined objective*" (ISO/IEC TR 19759, 2005) or "*combination of interacting elements organized to achieve one or more stated purpose*" (ISO/IEC/IEEE 15288, 2015).

From these definitions, it can be concluded that the concept of system consists of several core elements: *components* which can be people, objects, artefacts and procedures, *interactions* that link the components and *objectives* (operational needs or stated purpose) to be met by the system (i.e. the system finality). In addition, *environment* is another key element of a system. It includes information or any other exchange that the system may have with other systems. In industrial practice, a system is often considered as an end product or as the services it provides, for examples, aircraft or aircraft system.

A system is characterised by its complexity. Intuitively, the complexity of a system directly depends on the number of components of the system and of their interactions (system complexity = number of components x number of interactions). However, complexity is also a function of the number of states that the system can hold.

In most cases, a system always exists in a particular context or environment. Interactions may exit not only among components within the system, but also between the system and its external environment. So, one important but missed element in the above definitions might be "environment". The context of the system should be always taken into consideration during the development of a system and it should be the second important elements after the objective of the system. The guide to the Systems Engineering Body of Knowledge (SEBoK) (2014) used a chart (Figure 1-8) to globally present the fundamental elements and their relations.

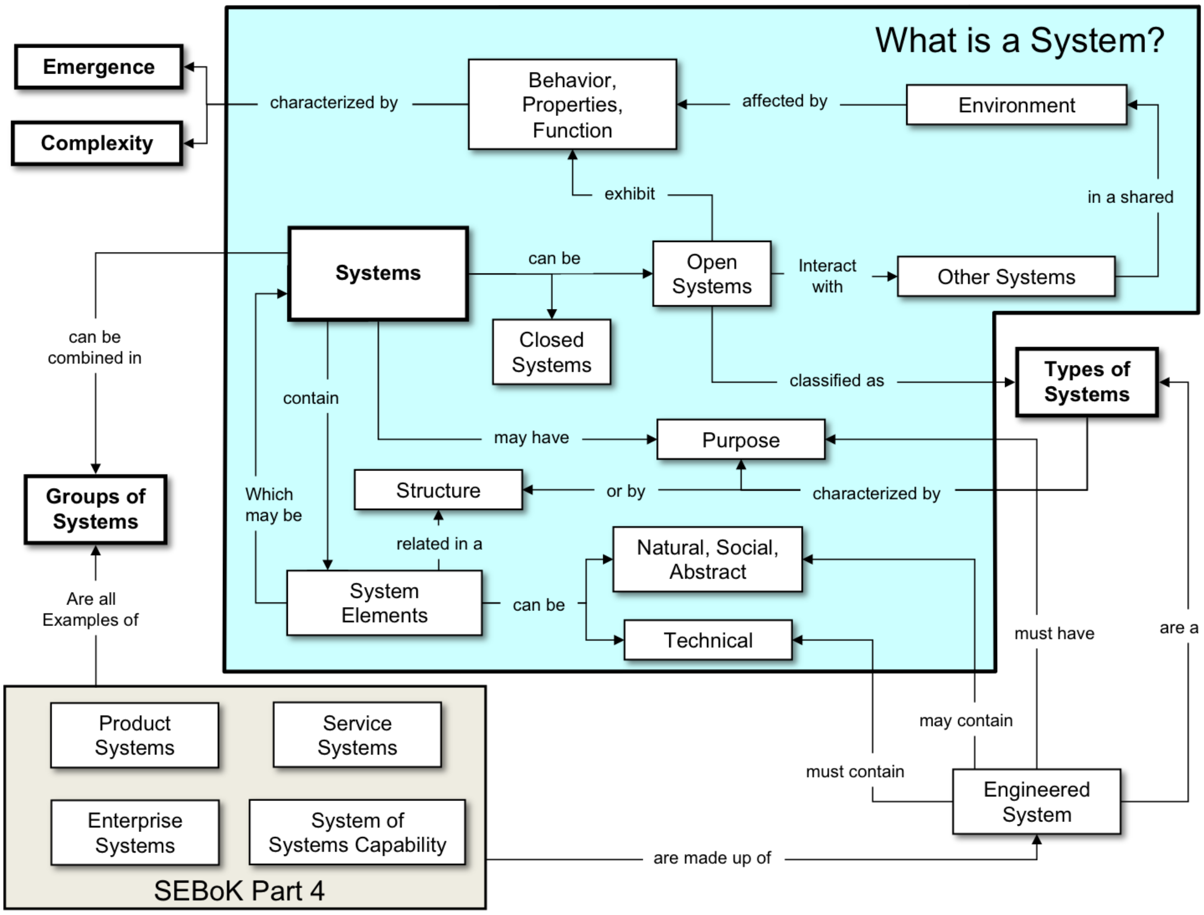


Figure 1-8. Fundamental elements of system (SEBoX, 2014)

Depending if there exist interactions between the system and its environment, systems can be classified as open systems or closed systems. Projects can be considered as open systems because they exist in an open environment and have to respond to the changing dynamics of situations to become much more adaptive than ever. A closed system has no interaction with the outside world. The two terms of complexity and emergence represent the challenges which drive the specification of the system. In addition, the SEBoK defines the engineered system as "*encompassing combinations of technology and people in the context of natural, social, business, public or political environments, created, used and sustained for an identified purpose*" (SEBoK, 2014).

In the systems approach, a number of relevant systems may be considered to help in achieving engineering or management tasks in more complex situations. In this case, the higher level system is a combination of sub-systems. When carrying out a project, it may be split up into a number of sub-projects. If they are executed in parallel, each of them can be considered as a sub-system in the system hierarchy. This leads to the more recent concept of system of systems (Ackoff, 1971; Maier, 1998). In addition, these elements in the systems approach can help the identification of the key elements for the development of the methodological framework of the proposed performance evaluation methodology.

1.2.1.2 Systems of Systems (SoS)

A system of systems (SoS) as defined by Ackoff (1971) is a collection of sub-systems that put their resources and capabilities together to create a more complex and synergetic system, which offers more functionality and performance than simply the sum of the constituent systems. Obviously, many industrial systems comply to this definition where sub-systems are physical systems (e.g. machines, operators, various types of resources, products, parts, etc.), information systems (e.g. data and information sources and flows, decisions, knowledge, etc.) and control systems (e.g. planning and decision centres, supervision modules, control & monitoring activities, etc.). For instance, it can be argued that any industrial supply chain is a system of systems.

According to Maier (1998), the concept of SoS differs from the one of monolithic system on the basis of five fundamental principles which are:

- Operational independence of components: if component systems of a SoS are separated, they can still work independently;
- Managerial independence of components: component systems are acquired separately and integrated to the SoS in which they can be managed independently;
- Evolutionary development: a SoS is never totally complete; its structure evolves according to addition, suppression or modification of component systems to fulfil the SoS goals;
- Emerging behaviour: constituent systems, evolving over time, have the ability of self-organisation in order to ensure the continuity of the mission of the overall SoS;
- Geographic distribution: component systems can be physically distributed in space.

Boardman and Sauser (2006) have later on revisited these principles and arranged them as follows:

- Autonomy: autonomous components contribute to the SoS finality.
- Emergence: the behaviour of SoS is not strictly prescriptive but emerges from the behaviour of component systems and stimuli of the SoS environment.

- Connectivity: the efficiency of a SoS depends on the connectivity and interoperability of component systems.
- Diversity: a necessary condition to the existence of a SoS is the heterogeneity of its constituents.
- Belonging: component systems decide to belong to the SoS on a cost/benefit basis, to get profit on their own and because they have trust in the mission of the SoS.

1.2.1.3 Needs and requirements

Stakeholder needs and requirements represent the views of each actor that are related to the particular decision problem. As stakeholder needs are often expressed in natural language, they need a structured process to elicit the needs into a defined set of more formal stakeholder requirements, which are the foundation of the project. According to the descriptions of SEBoK (2014), stakeholder requirements form the basis of system requirements activities, system validation and stakeholder acceptance. They also act as a reference for integration and verification activities. More importantly, they serve as means of communication between the project team, the management and the stakeholder community.

To understand the maturity of stakeholder needs and to explore how to improve the understanding based on the maturity, several steps are necessary to capture them. A representative method, namely the cycle of needs, is described by Faisandier (2011), as shown in Figure 1-9.

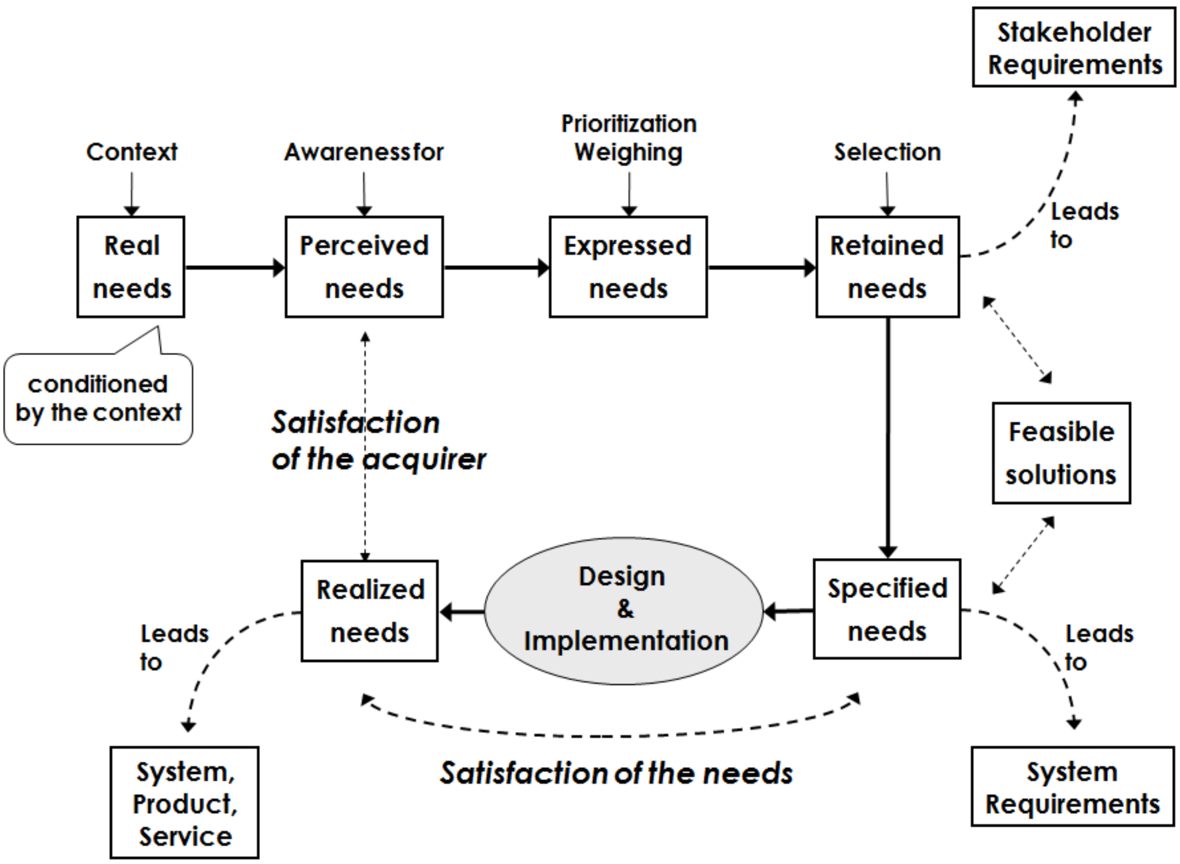


Figure 1-9. The cycle of needs (Faisandier, 2011)

Perceived needs are the judgements (for example, something is wrong or lacking) based on a person awareness; real needs are those that are hidden behind any perceived needs, they are seldom clearly expressed; expressed needs originate from perceived needs in the form of generic actions or constraints; then, retained needs are selected from the expressed needs; specific needs are translations of the stakeholder requirements to represent the views of the supplier; realised needs are the product, service or result produced with consideration of every specified need.

Stakeholders of a system may vary throughout the life cycle. To get a complete set of needs and requirements, it is important to consider all stages of the life cycle while identifying the stakeholders. For each stage, a list of all stakeholders that have interest in the future system must be identified. To collect stakeholder needs, expectations and objectives, some of the most common techniques are interviews, technical/operational/strategy document reviews, analysis of potential hazards and threats coming from the context of use of the system, feedback from verification and validation processes and, finally, review of the outcomes from the system analysis process (ISO/IEC/IEEE 15288, 2015).

1.2.2 Systems engineering processes

The term "systems engineering" has been defined differently in different fields. The definition proposed by the International Council on Systems Engineering (INCOSE) is often recognised as an authoritative description in this field. It states that *"Systems engineering is an interdisciplinary approach and means to enable the realisation of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, and then proceeding with design synthesis and system validation while considering the complete problem: operations, cost and schedule, performance, training and support, test, manufacturing, and disposal. Systems engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation. Systems engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs"* (INCOSE, 2015). To accomplish systems engineering tasks, a set of systems engineering processes is applied. An overview of the main phases and processes in systems engineering is shown in Figure 1-10.

Systems engineering processes form an iterative approach that goes through a series of steps from the highest level to the lowest level of the system in order to generate a preferred system solution. For each iteration, different alternatives are proposed, analysed and evaluated to get a trade-off result. Moreover, decisions on one subsystem affect other subsystems by integration factors. They also result in modifications in the specifications by adding new requirements on interfaces, constraints and functions.

Systems engineering activities span the entire project life cycle from exploratory research to concept and development. However, the systems engineering processes have evolved primarily to support the initial phases of a project. In this case, an efficient process for defining and developing large systems with consideration of project life cycle is essential.

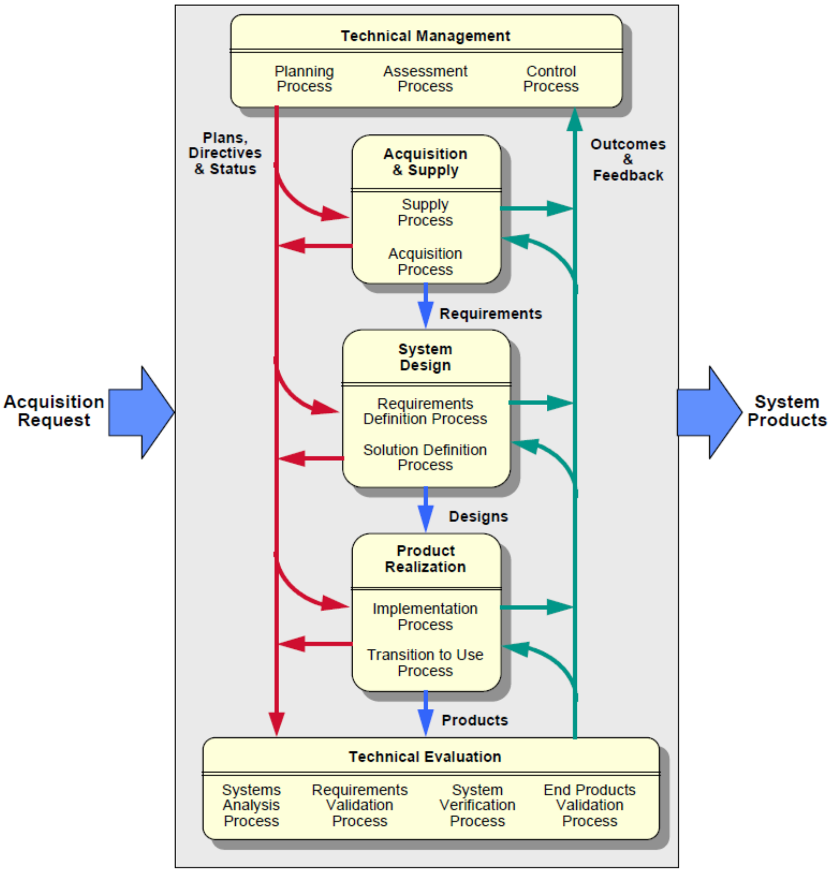


Figure 1-10. Systems engineering process overview (INCOSE, 2004)

1.2.1 Systems analysis

The various frameworks for systems engineering, and especially the ones from INCOSE and SEBoK, emphasise the importance of sound system requirements definition and engineering in the early phases of system design and analysis and the importance of requirements validation and system validation during technical evaluation, e.g. near completion of system development and build.

From the point view of problem solving, systems analysis can be considered as a technique that break down a system into components to analysis how well they work and interact to accomplish the objectives. In this context, enterprise modelling techniques are assumed as practical tools to model system components and their interactions.

Enterprise modelling is concerned with representing the function, behaviour, information, resource, organisation or economic aspects of a business entity (a single or a networked organisation) to understand, design or redesign, evaluate, optimise and even control the organisation and its operations to make it more efficient (Vernadat, 2003; 2002).

Enterprise modelling techniques are used to model functional aspects (business processes and enterprise activities), informational aspects (enterprise objects and their relationships), resource aspects (resource components, capabilities and roles), organisational aspects (organisational units, responsibilities and authorities) as well as temporal and causal constraints.

In almost all industrial projects, especially manufacturing systems, performance evaluation requires a good knowledge of the operational processes. Therefore, functional modelling is needed to describe activities to be executed or functions of the project final outcome.

Among the many methods used to model functional aspects of an enterprise, the ICAM DEFinition (IDEF) family of modelling languages has emerged as a suitable technique for years. It contains a set of modelling techniques to cover a wide range of uses, from functional modelling to data modelling, simulation, object-oriented analysis and knowledge acquisition. In the current research, IDEF0 or structured analysis and design technique (SADT) (Ross, 1977) and IDEF3 (Mayer et al., 1995) languages are selected to model all relevant elements around operational activities and processes of an industrial system. This is just a choice because one must be made; alternative languages such as BPMN (OMG, 2013) could have been used as well. A comprehensive summary of the IDEF0 and IDEF3 models is provided by (Vernadat, 1996) in the context of enterprise modelling.

IDEF0 is a functional modelling language for the analysis, development, reengineering and integration of information systems and business systems. The unit of an IDEF0 model is represented by a box which corresponds to an activity to be performed. It is associated with four types of arrows which are input (I), output (O), control (C) and mechanism (M) respectively. The activity box can be further broken down into several sub-activities at the lower level.

The IDEF0 or SADT proposes a simple and clear graphical representation form that corresponds to a hierarchical, modular and structured tool for the communications among team members. This tool depicts a functional relationship between a main function (or system or activity) and its constituent parts in such a way that the original function can be reconstructed by functional composition. This decomposition process is described in Figure 1-11.

The highest level (A0) represents the totality of the system. It is then broken down into different sub-systems (functions or activities), namely A1, A2, A3. The arrows of an ICOM box of each activity are interconnected to form a diagram. Each activity can be further broken down into activities at the lower level. For example, the activity A3 can be broken down into at least three elementary activities A31, A32 and A33 at the lower level.

The breakdown structure is complete once the lowest level is considered to be exhaustive enough for evaluation and implementation. In the current research, the functional decomposition is ended with the most detailed level where the corresponding elementary performance can be directly measured.

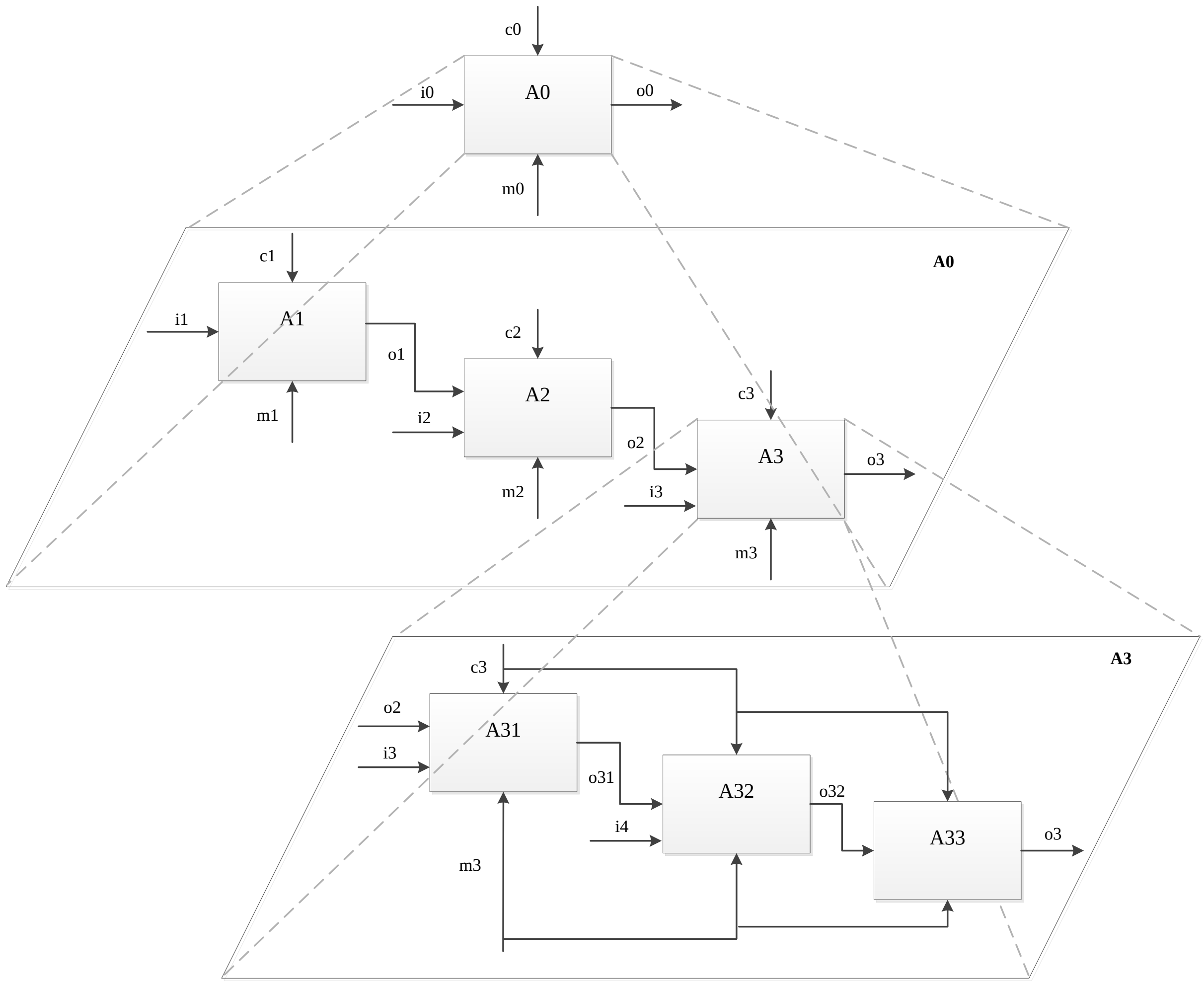


Figure 1-11. Decomposition with IDEF0/SADT (adapted from (Vernadat, 1996))

Once the overall system is decomposed into its different components, which represent its different functions with IDEF0 or SADT models, the following step is to identify the main operational process of each component to support further communication among users and performance measurement. In addition, the process description provides the evaluator with the basis for activity based objective identification and logical junctions among different activities for further operations in breakdown analysis. For this purpose, IDEF3, a graphic tool, is applied for operational process modelling.

IDEF3 describes a process as a sequence of units of behaviour (UOB), which represent activities (elementary steps of the process) or sub-processes (aggregated activity chains). These UOBs (represented by squared boxes) are connected by different links and junctions. There are three types of junction boxes in the IDEF3 model.

- AND (&) junction box states that all inputs (respect. outputs) of the UOB must be taken into consideration.
- OR (O) junction box indicates that one, several or all inputs (respect. outputs) of the UOB should be taken into consideration.

- XOR (X) junction box states that one and only one of the different inputs (respect. outputs) of the UOB must be taken into consideration.

Most SE methodologies or handbooks recommend paying special attention to risk management, either during system design or during system development (for instance, Chapter 6 of INCOSE, 2004). This concerns technical risks inherent to the system, environmental risks related to system operations or project management risks associated to the development of the system (or project).

In addition, it is obvious that the cost(s) of the system must be monitored at all stages of its life cycle. Life cycle cost analysis or system cost/effectiveness analysis methods are also recommended by SE methodologies and handbooks (for instance, Chapter 11 of INCOSE, 2004).

Finally, the value of the system can also be assessed to some extent during technical evaluation of the system by evaluating how well the system requirements have been met, by verifying system properties and by validating the system or its end products.

One of the goals of the BCVR methodology proposed in this thesis is to provide a contribution to support systems analysis in particular and systems engineering processes in general with a special focus on benefit, cost, value and risk analysis. More specifically, the BCVR approach can be a useful tool to support performance measurement and management of systems and projects.

The next section is therefore devoted to briefly review performance measurement and management systems and approaches.

1.3 Performance measurement and management systems

Managing industrial projects as well as engineering industrial systems are common and widespread activities in industry and service sectors. However, it is essential to assess how well these activities have been carried out.

Companies should therefore develop and implement tools for performance measurement and management to assess achievement of their objectives as well as of the stakeholder requirements and expectations in industrial projects. To be useful for the decision makers, such tools must be efficient and effective but not too much complicated. When managers have to make decisions, the key issue is to clearly identify and assess the existing trade-offs among the different performance criteria (Rodríguez et al., 2010). To do so, different methodological frameworks for performance management and decision support have been developed over the last three decades. The objective of this section is to analyse the key concepts and the main methods of performance measurement and management systems through various definitions and their application areas.

1.3.1 Performance

The process of performance measurement and management in industrial companies has experienced a significant development during the industrial age and it still continues nowadays (Shah, 2012). In this section, the basic elements of this concept are presented and analysed based on the results of the literature review. First, the definitions of performance in several research fields are reviewed. Then, the multidimensional characteristic of performance is presented.

1.3.1.1 Definitions

The concept of performance is widely used and is studied in different fields of research, but a universal and explicit definition is still missing (Franco-Santos et al., 2007). In the context of management, performance is directly linked to the achievement of organisational goals, i.e. objectives. This achievement can be understood in the strict sense (result or outcome) or in the broad sense of the process leading to the result (or action). To explain this concept, different terms are used by researchers in management science, such as "performance management" (Taticchi, 2010), "performance evaluation" or "performance measurement" (Merchant & Van der Stede, 2007) or "performance appraisal". In addition, other terms like "success" (Cantner et al., 2011) or "value" (Porter, 1998) also refer to the concept of performance. It can be noted that these terms are often interchangeably used in order to model the process of performance management.

In the project context, performance management is the application of different tools and techniques by using diverse resources to accomplish a unique, complex, one-time task within cost, quality and time constraints. Thus, these three aspects are the most important criteria for success in performance management. A classical vision is to define performance by means of a triangle, the summits of which are: cost, quality and time (Atkinson, 1999), as shown in Figure 1-12.

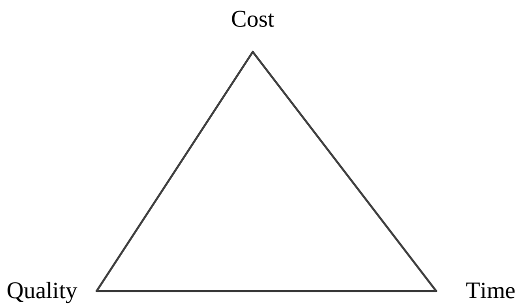


Figure 1-12. The iron triangle of performance (Atkinson, 1999)

This triangle expresses the triple constraint that must be considered in performance management. Although a decision maker wants to achieve success in all aspects, it is sometimes necessary to identify one or two of these objectives as being of special importance in the management decision.

A project for a charitable organisation with very limited funds would have to be always controlled under the initial budget. Therefore, cost must be the project manager's chief concern. For projects that are related to life critical systems, such as public transportation systems or medical projects, quality would be the dominant dimension. The success of a project to set up the booths at a trade exhibition, for which the date has already been announced, strictly depends on meeting the time objective.

The triangle also demonstrates that these three primary objectives are interrelated. Focussing on one or two summits of the triangle must sometimes be made at the expense of the remaining objectives in a trade-off decision (Lock, 2013). The performance, which is considered as the outcome of this trade-off decision, can be described by placing a spot with in the triangle boundaries.

From a human-centric perspective, performance can be defined by another triptych: organisation, competence and motivation (Vernadat, 1996) as shown in Figure 1-13.

Figure 1-13. Performance triangle (Vernadat, 1996)

It can nevertheless be determined by another framework as well: motivation, opportunity and ability (Siemsen et al., 2008). In this model, motivation represents the individual willingness to act, opportunity refers to the environmental or contextual mechanisms that enable the action and ability captures the individual skills or knowledge related to the action.

In the industrial context, performance is more commonly defined by the concepts of efficiency and effectiveness (Neely et al., 2005), efficiency, effectiveness and relevance (Jacot, 1990) or efficiency, effectiveness, effectivity and relevance (Senechal, 2004; Bescos, 1995).

Effectiveness is the relation between results and objectives in order to indicate that the system is doing the right thing. *Efficiency* is the relation between the results and the resources used to achieve them to evaluate if the system is doing things right. Then, *relevance* is the relation between the objectives and the resources mobilised to measure if the resources used correspond to the predefined goals of the system. Finally, effectivity is the balance of the three elements: objective, resource and results to present the finality of the system. Figure 1-14 presents the triptych of performance with efficiency, effectiveness and relevance.

From the triptych, it can be considered that the concept of performance has a close relationship with objective. Lebas (1995) mentioned "*Performance is about deploying and managing well the components of the casual model(s) that lead to the timely attainment of stated objectives within constraints specific to the firm*". This link is also emphasised by Folan et al. (2007): "*It is always made with a relevant objective in mind (thus, we commonly assess a company as per some set future vision on what the company wants to achieve, not on the objectives of some other body that is not the company)*".

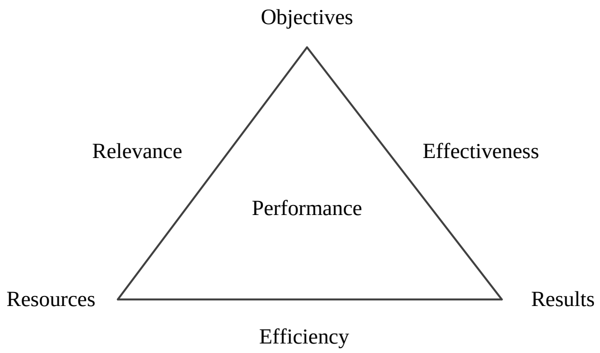


Figure 1-14. Triptych of performance: efficiency, effectiveness and relevance

In the first instance, the notion of performance seems to meet both effectiveness and efficiency, but it is not necessary to involve these two terms at the same time. In this case, three postulates characterise the industrial performance nowadays (Berrah, 2013).

The first two postulates relate to the definition of "performance". The first one is called "Taylorian". Performance is synonymous with efficiency which means the performance of equipment or the productivity of direct labour (Kanigel, 2005; Pouget, 1998). The second one in today's practice is named as "neo-Taylorian". Performance is evaluated not only according to the efficiency of the means of production, but also depending on the effectiveness and the effectivity of the implemented process (Bullock & Deckro, 2006).

The second postulate also covers the multi-criteria characteristic of the concept of "performance". With the revolution of the industrial systems and their environment, to progressively integrate the technical criteria of quality and time (Lebas, 1995) in addition to cost, other criteria, for examples innovation, design, equity and durability (Brunel, 2012; GRI, 2011; Sikdar, 2003), have been introduced to complete this triptych of performance.

The third postulate relates to the monitoring mode of "performance". The multi-criteria characteristic of performance indeed generates an arbitration issue among various actions to be taken; for example, the time constraint and the resources to be considered. The performance monitoring has evolved from an additive model in which the overall performance is the sum of local and independent performances (Johnson, 1975) to a more complex model where the overall performance is always a compromise among local and dependent performances (Clivillé, 2004). In this context the concept of performance becomes a synonym of improvement (Berrah, 2013).

1.3.1.2 Classification

At a high level, performance can be classified into two categories: financial and non-financial (Dossi & Patelli, 2010). The former one relates to the performance from the accounting point of view. This aspect of performance has been widely studied. The performance is measured in monetary terms (Horngren et al., 2012). The most commonly applied measurements are: the revenue, the return on investment (ROI) and the economic added value (EVA). The studies in this field have resulted in methods such as “Activity-Based Costing (ABC)” (Cooper & Kaplan, 1988) and “customer profitability analysis” (Abdel-Maksoud et al., 2005).

The non-financial performance is based on the concepts of time (George Stalk, 1988), quality (Deming, 1982) and flexibility (Slack, 1983). In addition, the concept of performance appears to be polysemic. It alternatively refers to various translations, such as satisfactory in the economic field (North, 1994), execution in the legal field (Peters, 2008) and efficiency in the organisational field (Richard et al., 2009).

1.3.1.3 Characteristics

On one side, performance of an industrial system (project or process) can be assessed from multi-viewpoint, multi-level and multi-criteria. Performance excellence in part of these aspects cannot guarantee the success of the system. Effective performance can be obtained by simultaneously achieving all stakeholder requirements. Moreover, performance measurement results change across the organisation hierarchy and evaluation criteria.

On the other hand, the concept of performance is contextual and relative. Indeed, the meaning of performance depends on the objective to be met. It is also influenced by the moment, the way and the conditions under which it is measured and interpreted.

In this context, the concept of “industrial performance” is considered as multidimensional (Shah, 2012) and relative (Li et al., 2015) in nature.

1.3.1.3.1 Multi-viewpoint

Different stakeholders, such as investors, shareholders, creditors, suppliers and customers, consider the performance in different ways because of the diversity of their interest towards the organisation. Therefore, it is the responsibility of the enterprise to identify and meet the expectations of its stakeholders (Atkinson et al., 1997). Many researchers have considered this characteristic to improve the performance (Marques et al., 2010; Mauchand et al., 2012; Neely, 2007). Regarding industrial problems, a direction that can be further explored is to consider the network of partners as a system of systems and investigate the study on performance in this field.

1.3.1.3.2 Multi-level

Performance cannot only result from the selection of a set of balanced criteria. It should be also classified into strategic, tactical and operational levels (Gunasekaran et al., 2001). These levels reflect different hierarchical degrees within the company and different time horizons where they have their own requirements on decision and measurement (Rushton et al., 2010).

As shown in Figure 1-15, Jacot and Micaelli (1996) proposed a multi-level structure to conceptualise the performance at different levels. Each level has its own objectives, criteria and performance.

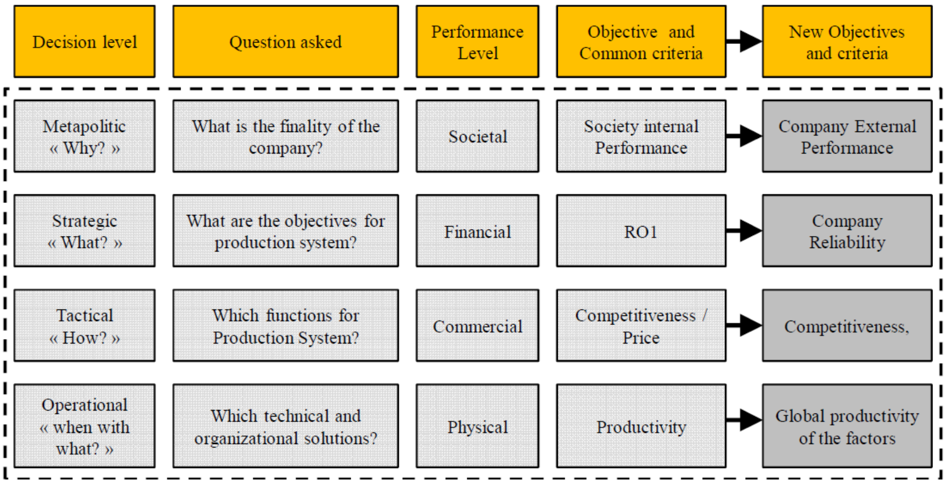


Figure 1-15. Multi-level structure of performance (Jacot & Micaelli, 1996)

1.3.1.3.1 Multi-criteria

The multi-criteria aspect of performance introduces an arbitration issue among various actions concerning the time constraints and resources. Besides, as Taylor's productivity can be optimised by maximising the use of resources (Kanigel, 2005), the performance cannot be improved (Deming, 1982). The reason is that the variety of criteria involved in its definition affects the achievement of the implemented actions and the elements are in interaction with one another.

It is obvious that performance measurement requires a multi-criteria approach where the elements to be considered depend as much on internal non-financial arbitration than on accounting/financial measurements. The concept of performance can be legitimately extended to the achievement of non-financial objectives in an operational nature.

1.3.2 Performance indicators

Performance are measured and evaluated through a set of evaluation indicators. They play a central role in the continuous improvement loop or PDCA (Plan – Do – Check – Act) cycle of the Deming’s Wheel (Deming, 1982). They reflect the degree of achievement of objectives and feed the decision making process regarding the choice of corrective actions to be taken. This calls for an analysis of definitions and functionalities of performance indicators.

1.3.2.1 Definitions

Broadly speaking, Bitton (1990) stated that “*an indicator is an objectified measurement*”. In the context of performance management, the Association Fran çaise de Normalisation (AFNOR) defined a performance indicator as *“a quantified data which measures the effectiveness and/or efficiency of the whole or a part of a process or system, compared to a standard, plan or objective, determined and accepted within the organisational strategy*” (AFGI, 1992). Similarly, Fortuin (1988) described a performance indicator as “*a variable indicating the effectiveness and/or efficiency of a part or whole of the process or system against a given norm/target or plan*”. These definitions are built based on an extension from efficiency to effectiveness. So, except the objective, measurement and strategy, the global aspect of performance is highlighted by these definitions.

1.3.2.2 Functionality

A performance indicator is a key element in a feedback loop mechanism supporting a decision making process (Berrah, 2002; Berrah, 2013; Lohman et al., 2004), as shown in Figure 1-16.

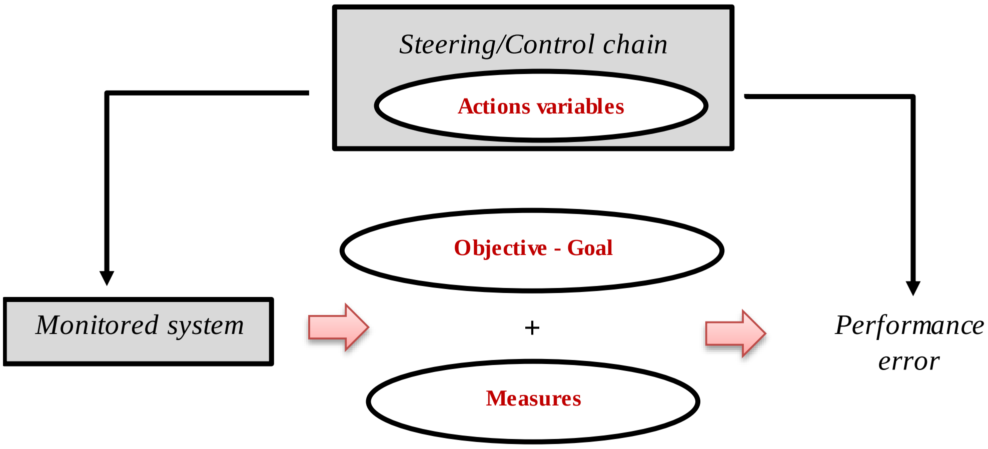


Figure 1-16. Feedback loop and components (Berrah, 2013)

This feedback loop consists of the monitored system, the objective (or goal), measures, performance error and a control chain. In this context, the performance indicator is not only a measurement but also an association between the negotiated objective, variables of decisive actions, means of action and a measurement of effectiveness (Berrah & Vernadat, 2002).

It can be concluded that performance indicators not only reflect the efficiency and effectiveness of the project (or system), but also provides feedback for decision makers in continuous improvement and objective accomplishment.

Most industrial firms attempt to satisfy demand, increase quality, decrease overall costs, meet due dates and control implied risks. Performance indicators, such as customer satisfaction, quality control, on-time completion, cost, safety or profitability together with innovation, are applied to determine competitive advantage and to evaluate the performance of an industrial project (Yun et al., 2016).

Due to the fierce competition and increasing business evolution, companies need ever more up-to-date performance information to evaluate their industrial project, process or product. This leads to the proliferation of performance evaluation indicators and data overload for decision makers. In addition, some measurements are time-consuming, which reduce the efficiency of decision making.

It is considered that the performance of an industrial system can be comprehensively measured and managed by following its overall benefit, cost, value and risk. Their definitions in project and system management are reviewed in the following section.

1.3.3 Notions of benefit, cost, value and risk in project and system management

Indeed, to evaluate the global performance of an industrial project, the management wants to know what will be the expected benefits, the overall cost, the value it will bring and the implied risk. In this context, it turns out that the performance of an industrial project can be globally measured and managed based on four essential dimensions: benefit, cost, value and risk (Vernadat et al., 2013). This is confirmed in practice where most managers must report the progress of their projects in terms of these four elements together with time and delay. If they can be aggregated into meaningful project management information, they provide the basis for an ideal project management dash board.

1.3.3.1 Concept of benefit

The existing definitions of benefit can be categorised within two groups: financial benefits and non-financial benefits. The former deals with financial gains (i.e. profitability) and is expressed in monetary terms. The latter relates to something that promotes well-being or intangible added-value and can hardly be measured in any units.

In most cases, benefit is defined as a positive difference between cash inflows (cash receipts) and disbursement flows (cash expenditures). Thus, it has a monetary unit in the context of accounting. While referring to project management, Atkinson (1999) defines benefit as a criterion which could be used to measure the success of the project post implementation, such as increased profits, social and environmental impact, personal development and so on. In this case, it is not necessarily expressed in monetary unit.

In this thesis, benefits represent tangible or intangible gains of a project or a system, i.e. gains in their broad sense. They will be expressed in literal terms.

1.3.3.2 Concept of cost

Cost is a major concept that expresses the total expenditures incurred and caused by a company activity or decision (e.g. TCO for Total Cost of Ownership). In a generic context, cost is defined as a resource consumed to achieve a specific objective (Laitinen, 2014). A cost is usually measured as the monetary amount that must be paid to acquire goods or services (Horngren et al., 2012). It can be either the expenditures incurred in the past (an actual cost) or the result of a calculation that is based on assumptions and approximations (a budgeted cost).

We only consider the relative cost of products, services, company activities or projects. The sum of the costs for obtaining all the required functions of a product or a service is equal to the total cost. For example, the total cost of an entire supply chain includes costs in procurement, production and delivery stages. They can be further detailed into costs of component design, production set-up, component purchasing, transportation, product design, production ramp up and inventory holding (Zhang et al., 2016).

1.3.3.3 Concept of value

The value generated by an industrial system becomes a critical concern because companies are subject to value creation for stakeholders and to value differentiation regarding the competition. However, value is still a vague term in the technical literature as well as in technical circles and the precise definition is still in its infancy.

As its stands today, the existing definitions of value can be categorised in two groups: financial value and non-financial value. In addition, in the context of human sciences, value can be defined as a principle to which a person or an organisation unit believes in and adheres to.

AFNOR (2009) defines value in the product context as a judgment made on product by users on the basis of their expectations and motivation. More specially, the value increases when the needs increases or the expenditure related to the product decreases (Yannou, 1999).

Nevertheless, the definition of value is not absolute but relative and subjective. Value is a polysemic term and therefore, like all polysemic words, the clue to its meaning is given by the context (Bourguignon, 2005). With the evolution over time, it can be perceived differently by different stakeholders who are in different situations. For example, from an idea in the design office, the value of a product becomes commercial for the manufacturer through its physical realisation in production, and then the value will be called acquisition value for the customer. During the use phase of a product or a service, it will become a use value. Furthermore, all stakeholders cannot be considered at the same level (Garengo et al., 2005). They should be recognised at different levels (corporate, business units, business process and activities) of performance measurement. At each level, different stakeholders do not possess the same degree of influence on the project performance.

1.3.3.4 Concept of risk

Risk is often interpreted as a threat. ISO standard (ISO Guide 73, 2009) defines risk as: *effect of uncertainty on objectives*. Therefore, risk can be considered as an event which, if it occurs, will prejudice the objective achievement of a system or project. It is then a potential danger that has a probability to take place in a particular activity or in a particular context. For a company, risk is the likelihood of a nuisance (or danger) that could affect the assets or the results. Unintended but partly predictable, it encourages behaviours of protection, transfer and insurance.

Risk can be characterised by a triplet “occurrence, effect and state” (Gourc, 2006). *Occurrence* allows to classify risks in their origins by specifying the conditions and probabilities of occurrence. *Effect* refers to manifestations associated with its occurrence, the types and measurements of the impacts. *State* describes the evolutionary nature of risk. In a project context, a risk occurrence, which impacts project on duration and cost, may introduce the modifications of the project structure and existing tasks (Marmier et al., 2013).

Because it is interpreted differently in different application fields, risk is treated according to variable modalities. So, there is no unique definition for risk. Sienou (2009) confirmed the polysemic nature of this concept and provided an ontological discussion in his doctoral thesis.

In any case, a risk, which is the probability of occurrence of an event, is the consequence of one or more risk factors. If it occurs, it will have an impact in the form of consequences. For example, in a traffic accident, some risk factors are: dangerous driving, abuse of alcohol or narcotic substance, fatigue or difficult weather conditions. The event will be the occurrence of an accident. The impact or consequences may be property damage, people who are injured or even be killed and financial or criminal convictions of agents involved in the event.

1.3.4 Performance measurement and management methodologies

It is useful to recall that methodologies for performance measurement and management and their corresponding concepts are constantly evolving. This evolution, from the one-dimension vision (only based on financial aspects) to the multi-dimension vision (considering multi-stakeholder, multi-level and multi-criteria), was largely attributed to industrial practices and significantly changing market places in recent years.

From a generic point of view, a performance measurement and management methodology usually covers the following main points: (1) definition of the research scope concerned by the methodology, (2) expression of the decomposition links between the fundamental and elementary objectives, (3) definition of the way in which the associated "elementary" performances are expressed and (4) choice of the aggregation tool(s) to calculate a global performance expression (Berrah & Foulloy, 2013).

1.3.4.1 Evolution of methodologies

The evolution of the methodologies in performance measurement and management can be divided into several important periods: productivity management, budget control, integrated performance measurement and integrated performance management (Bititci et al., 2012) as shown in Figure 1-17.

The first two periods can be categorised by specialisation of workers (Taylor, 1911) and the large-scale production (Ford, 1922). During these periods, product demand exceeded the capacity of production. This made industrial companies focus on sales and improving productivity without much concern to customers (Neely, 2007). In this context, companies cared only to financial performance indicators (Johnson & Kaplan, 1987) such as cost, productivity and return on investment.

The following period is categorised by the introduction of other dimensions of performance and corresponding evaluation criteria. This integration brought the multidimensional aspect of performance and it has complexified performance management. Then, this situation led to the development of integrated performance measurement methodologies, such as Balanced Scorecard (BSC) (Kaplan & Norton, 1992), supply-chain operations reference (SCOR) (Lambert et al., 1998), ECOGRAI (Bitton, 1990), Strategic Measurement and Reporting Technique (SMART) (Cross & Lynch, 1988) or Performance Prism (Neely et al., 2002).

In the last period, researchers tried to solve the problem of setting up performance indicators to manage performance (Bourne et al., 2000). This focus led to integrated performance management in which performance measurement is established as a process. In addition, researchers studied performance in several areas, such as research and development (R&D), innovation (Chiesa et al, 2009; Chiesa & Frattini, 2007), supply chain and collaborative networks (Clivillé & Berrah, 2012; Ganga & Carpinetti, 2011) and small and medium-sized enterprises (SMEs) (Garengo et al., 2005).

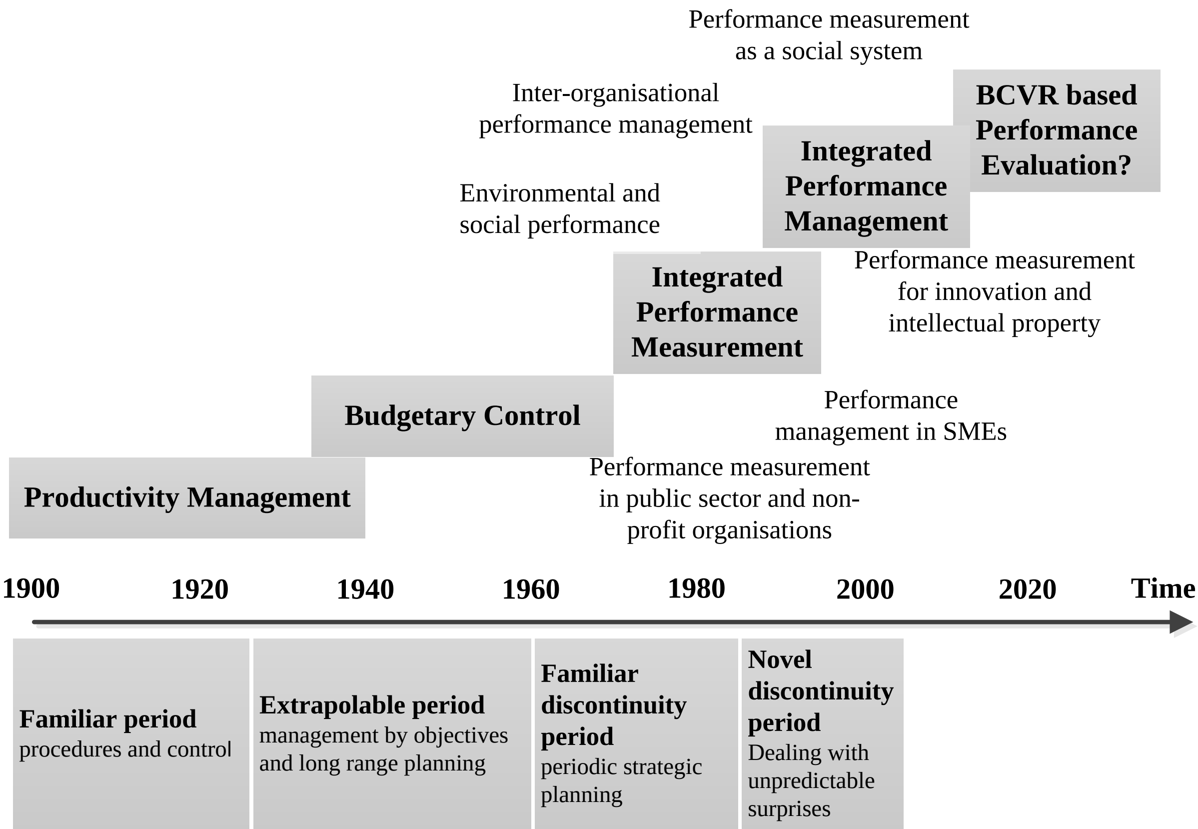


Figure 1-17. Development of the performance measurement approaches (adapted from (Bititci et al., 2012))

In summary, performance measurement and management methodologies evolved with business trends. Consequently, the problem of performance measurement and management becomes ever more challenging due to the huge information flow in today's fluctuating environment. In addition, other aspects such as performance in multicultural context, small and medium enterprises, green supply chain and collaborative networks are still developing. Besides, the trend that companies want to evaluate everything made performance measurement and management more complicated. Therefore, a simple but still effective, and possibly visual, methodology for performance measurement and management would be welcomed if it could be developed.

1.3.4.2 Comparison of the main methodologies

This part is devoted to a synthesis of the main existing methodologies of performance measurement and management. The objective is to identify relative strengths and weaknesses of these systems to identify the requirements to be considered to develop a new methodological framework.

So far, many performance measurement and management methodologies have been developed. Some researchers have produced summaries on the main exiting frameworks (Mauchand, 2007; Shah, 2012). Building on their analysis, a new comparison based on some of the key criteria discussed in this chapter is presented in Table 1-2.

Table 1-2. Comparison of the main performance measurement and management methodologies

	Objective analysis	activity analysis	Multi-stakeholder aspect	Multi-criteria aspect	Multi-level aspect	Benefit evaluation	Risk evaluation	Cost evaluation	Value evaluation	Decision support
ABC (Activity-Based Costing) *(R. Cooper & Kaplan, 1988)*		√						√		
SMART (Strategic Measurement Analysis and Reporting Technique) *(Cross & Lynch, 1988)*	√			√	√					
BSC (Balanced Scorecard) *(Kaplan & Norton, 1992)*	√	√	√	√				√		
SCOR (Supply Chain Operations Reference) *(Bolstorff & Rosenbaum, 2003)*	√	√					√	√		
Performance Prism *(Neely et al., 2002)*	√		√	√						
ECOGRAI *(Bitton, 1990)*	√	√								√
IPMS (Integrated Performance Measurement Systems) *(Bititci et al., 1997; Suwignjo et al., 2000)*	√		√	√	√					
IPMF (Integrated Performance Measurement Framework) *(Medori & Steeple, 2000)*	√			√						
QMPMS (Quantitative Models for Performance Measurement System) *(Suwignjo et al., 2000)*	√			√						√

In terms of cost evaluation, the ABC method presents the advantages of analysing the impact of design choices on product cost. But the limits are noted on its applicability to new activities or any new event such as induction of specific raw materials that are provided by a new supplier. In addition, the dimension of cost can also be evaluated by the BSC method and the SCOR framework.

The concept of value is not mentioned in the BSC, SCOR and ECOGRAI methods although they proved to be a potential support to value evaluation. Based on this comparison, most of the methodologies take into account the multidimensional aspect of performance. But they do not offer mechanisms to assess the contributions of multiple stakeholders. In addition, risk engineering and value assessment have not really been addressed, and most of the selected methods are rarely linked to decision making process.

In this context, it can be concluded that none of the existing methods really provides a comprehensive and integrated methodology that can comprehensively measure and manage performance of an industrial system. So, a new methodology for industrial performance measurement and management should be developed to meet this requirement. However, it should be noticed that there is no universal methodological framework for performance measurement and management. In fact, such evaluation system always depends on the particular organisation and desired objectives of selected given company, the allocation of tasks and even the responsibilities that are defined in the organisational chart. In other words, the performance evaluation methodology should be appropriate for the special project context, decision problem and decision maker preference(s).

1.4 Conclusion

This chapter has presented and reviewed the definitions, concepts and approaches related to existing methodologies and tools for performance measurement and management in industrial projects. It has been divided into three parts: (1) basic concepts and methods around project management methodologies; (2) essential concepts and processes of systems engineering and (3) concepts and methodologies for performance measurement and management. From the review, it can be concluded that:

- To ease project management, a project is divided into different phases along its life cycle. In each phase, different stakeholders are involved and different processes are integrated in order to have a comprehensive control of the project. Therefore, identification of stakeholders, project life cycle and phase analysis should be indispensable elements in the start-up stage for performance measurement and management in industrial projects.
- Although different performance measurement and management methodologies were developed, it is still necessary to propose a new methodology to meet the characteristics of performance with an effective and comprehensive evaluation framework. As the dimensions of benefit, cost, value and risk are the most common and important aspects while evaluating an industrial project, it is considered that the new methodology can be developed based on these dimensions.

Since the aim of this chapter was to describe the major concepts and methods used in performance measurement and management in industrial projects, the following chapter is dedicated to introduce the key elements and the global structure of the proposed methodology.

CHAPTER II: BCVR PERFORMANCE EVALUATION: KEY CONCEPTS AND FRAMEWORK

According to practitioners in business and industry, and as supported by literature, it is claimed that the overall performance of an industrial project can be comprehensively and synthetically evaluated by a more effective and efficient framework, which should be based on four dimensions: benefit, cost, value and risk. The purpose of this chapter is to present the work carried out on these fundamental concepts and the global structure of the performance evaluation methodology proposed. The structure adopted for the chapter is depicted by Figure 2-1.

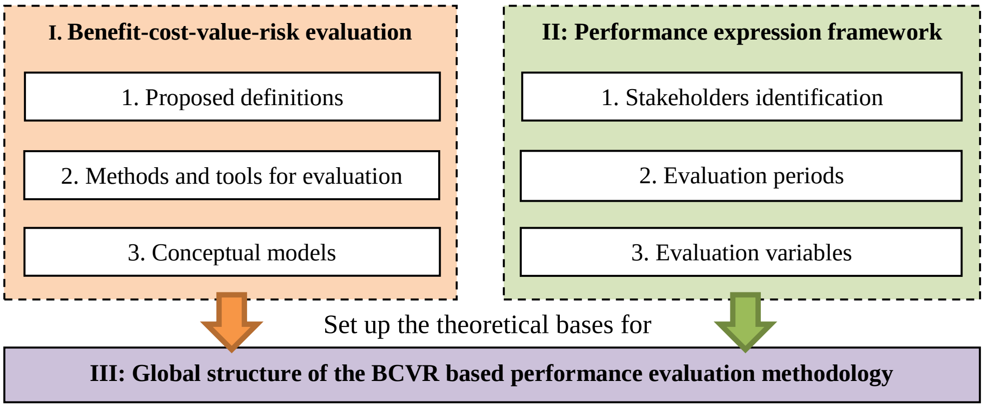


Figure 2-1. Global structure of Chapter II

This chapter is divided into three sections. Firstly, the conceptual analysis of the four basic dimensions of the proposed methodology, including the adapted definitions and underlying conceptual models, is presented to set the basis of the proposition. Then, the proposed performance expression framework articulated on the basis of three perspectives (namely stakeholders, evaluation periods and evaluation variables) is explained to define another fundamental aspect of the methodology. Finally, based on these two theoretical bases, the global structure of the proposed performance evaluation methodology is described to show the main steps and the relations among them. For clearer explanation and better understanding, a familiar example of performance evaluation concerning a Ph.D. thesis project is used to illustrate the proposed concepts and methods.

2.1 Concepts of benefit, cost, value and risk

Because they are the essential elements that we propose to consider for comprehensive performance measurement and management, it is important to analyse these four dimensions for the purpose of evaluation. In this section, the four axes are analysed in terms of definition, classification, evaluation methods and conceptual models. The objective is to present the basic elements used for the development of the proposed methodology.

As mentioned earlier, for any project, including carrying out research work for a Ph.D. thesis, it is essential to state what are the benefits of the work (e.g. relevance and utility of the Ph.D.), to monitor project costs, to have a good assessment of the value of the work (e.g. importance and timeliness of the research results of the Ph.D. thesis) and to regularly identify, evaluate and mitigate risks all over the project to make sure that project objectives are met in the most efficient and effective way.

2.1.1 Concepts analysis

As introduced in the previous chapter, the concepts of benefit, cost, value and risk are popular terms that have been widely used in almost all practice and research contexts. As for the concept of industrial performance, their definitions vary among different fields of application and it is hard to identify standard definitions that can be adapted to universal situations. Therefore, the specific definitions of benefit, cost, value and risk adopted in this document must be firstly presented and justified regarding the particular research context of the proposed methodology.

2.1.1.1 Concept of benefit

In the literature review of Chapter I, it has been shown that the concept of benefit is often defined in monetary terms, usually from an accounting perspective. One of the most practical analysis methods is the well-known cost-benefit analysis (CBA) method. Its theoretical origins date back to issues in infrastructure appraisal in France in the 19th century. It is a systematic approach used to estimate the strengths and weaknesses of project or system alternatives. Its theory and practice remained divergent until the formal requirement that costs and benefits be compared was enforced in water-related investments in the USA in the late 1930s (Pearce et al., 2006). The method has recently been revisited by Mishan and Quah (2007) to evaluate the opportunity of one or a number of projects. The main purposes of applying CBA are twofold (Nas, 1996):

- To decide whether a project will be or is worthwhile, in other words, answer questions:
    a. Should we invest in this project?
    b. Which of two alternative projects should we support?
        i. Which project will give the best pay off per euro invested?
        ii. Which project will generate the highest monetary value?
- To assess whether a project has been worthwhile

However, unlike the usual definitions in financial terms like in the CBA method or other theories, the dimension of benefit used in the proposed approach is in many cases not defined as a quantitative monetary measurement, but in qualitative terms to state the expected gains or business advantages of a project or system. The proposed definition is therefore the following:

BENEFIT
A qualitative list of potential advantages or gains for a stakeholder compared to an objective that is set beforehand for the realisation of an industrial project or system.
Examples (for a PhD candidate in a doctoral programme): • Acquisition or improvement of scientific skills attested by a Ph.D. diploma • Potential opportunities for professional future in research • Initiating a scientific reputation in a specific field (attested by a publication list)

According to the definition of project success, the stakeholder objectives must be accomplished by the end of a project. But the benefit of a project is not predefined and is not necessarily satisfied.

This proposed definition can be extended based on several considerations. First, no benefit can be realised without a change or evolution in the current state (Serra & Kunc, 2015). This change is materialised by the final outcome of the project. In addition, the benefit should be owned by or assigned to a certain stakeholder (person or organisation) made responsible for realising it (Chih & Zwikael, 2015). The benefit will not accrue without a specific owner, because nobody will be interested in using the project outcome to capturing the benefit.

Benefit can be tangible or intangible. Tangible benefits, which are always measurable and are in numerous cases financial, can be estimated before the start of a project and measured at the end. Intangible benefits, which are often related to non-financial and subjective aspects, may either be measurable (for example, time and cost savings resulting from using a new IT tool) or non-measurable and qualitative (for examples, the company's reputation or a technical feature of a product bringing competitive advantage). They can be listed before the project starts and can only be ascertained at the end.

It follows from this discussion that, because any kind of benefits cannot be systematically expressed in measurable units to become an estimation indicator, they will be expressed in the form of literal expressions in the proposed methodology and listed as potential advantages or gains, as indicated in the above mentioned definition. It can however be noted that some measurable benefits (for instances, productivity gains or time reduction of some activities) can be defined as elements of the value axis, if it makes sense to include them in the definition of a value expression (see section on value).

In other words, it is proposed that the benefit axis will only be qualitatively analysed while evaluating the performance of an industrial project or system. However, in many cases, these advantages or gains could be transformed and computed in monetary terms (such as profits) if necessary for further evaluation (for instance, using the cost-benefit analysis) or utilisation in other applications that are out of the scope of the proposed methodology.

2.1.1.2 Concept of cost

In the current research, only the costs which are related to the production and distribution of products, services, company activities or projects are taken into consideration. For almost all cases, it is supposed that the sum of the elementary costs for obtaining all the required functions of a product or a service is equal to the total cost, as shown in Equation 2-1.

$$\mathrm{C}_{total} = \sum_{i=1}^{n} C_i\,,\ i \in n \qquad (2\text{-}1)$$

Where, C_{total} is the overall cost of a project and C_i is the elementary cost of one component in the cost structure of the project.

The proposed definition of cost on the cost axis is:

COST
Total expenses for the design, production, distribution and acquisition to deliver the final result (a product, service or deliverable) of a project, process or system.
Examples (for a PhD candidate in a doctoral programme): Living expenses; Material and equipment; Training; Scientific communications

As shown in the literature review, the dimension of cost is always defined in financial terms in the proposed methodology. It means that the cost of an industrial project is quantitatively expressed and evaluated in monetary terms. So, the challenging point regarding this axis is not the proposition of an adapted definition, but the identification of the different measurable elementary costs that can comprehensively represent the overall cost of the project.

To ease the cost identification of a specific domain or area of activities (e.g. management, accounting or else), a classification of usual costs can be developed to distribute actual costs in different categories according to some common characteristics. Depending on the purpose of the analysis, there are several possible classification methods. Table 2-1 presents some typical classifications of costs that are applicable to a specific product, service or system.

Table 2-1. Example of cost classification

Purpose	Categories	Definitions	Examples
To describe the allocation of the overall costs	Variable cost	Expense varies when the volume of corporate activity changes	Manufacturing cost; Transportation cost; Packaging cost
	Fixed cost	Expense does not vary with the business size during a specified period	The amortisation of real estate assets (for example, buildings and machines)
	Semi variable cost	Expense includes both a fixed part and variable part for a fixed period	Electricity and heating charges; Maintenance cost
To prepare external financial statements	Manufacturing cost	The total consumption of used resources in a product manufacturing process	Direct material costs, direct labour costs and general manufacturing costs
	Non-manufacturing cost	Other expense in addition to the manufacturing	Administration cost; Marketing cost
To assign the overall costs	Direct cost	Expense that can be completely attributed to a specific project, product or service	Raw material expense that is included in the product or service; Labour hours that are allocated to the production of the product or service
	Indirect cost	Expense that may concern several projects, products or services.	Administration expense; Monitoring and maintenance fees
To make decision	Differential cost	Difference in expense among different alternatives	Differential cost of an alternative proposal
	Opportunity cost	A potential benefit or income that is given up as a result of selecting an alternative over another	Opportunity cost of choosing a mode of transportation
	Sunk cost	Expense that has already incurred and cannot be changed by any decision	The investments in the facilities, machines and buildings
	Relevant cost	Expense that varies with the managerial decisions	Payable wages to the employee in the context of plant closure
	Non-relevant cost	Expense that does not vary with the managerial decisions	Prepaid rent for the buildings in the context of plant closure

It is important to note that the classifications are not mutually exclusive. An elementary cost can be classified differently in numerous problems. Depending on the particular context, the evaluator can choose the adapted category to express the interested elementary costs for performance measurement and management. As described in the previous chapter, project management is accomplished through the appropriate application and integration of five process types: initiating, planning, executing, monitoring & controlling and closing.

In the current research, a classification of usual costs that can occur in the course of a project is proposed based on these five project management process types (Figure 2-2).

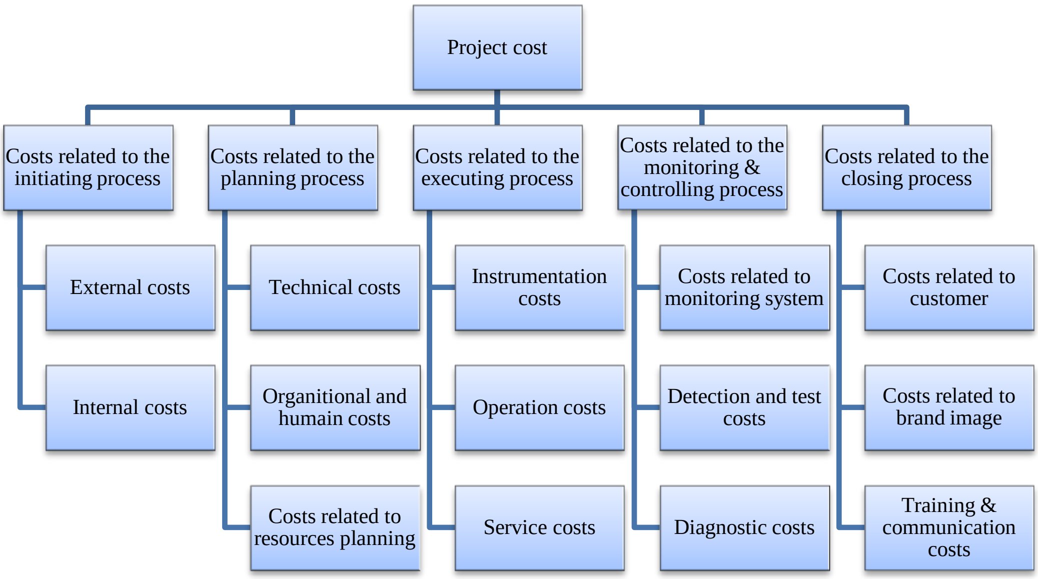


Figure 2-2. Cost classification by project management process type

The aim of this classification list is to be used as a check-list by analysts when they will have to identify the cost structure that they want to take into consideration on the cost axis of the methodology. The detail of this proposition can be found in Appendix A.

2.1.1.3 Concept of value

The literature review shows that the concept of value has a polysemic nature as well and is not yet stable. Broadly speaking, it can be divided into two categories: financial and non-financial value.

The former can be expressed as "*the monetary worth of something*" (for example, the price of a product or the economic profit generated by business activities). In this context, it has a similar signification as "income" that is widely used in the field of finance and accounting.

The latter can be described as "*the relative worth, utility or importance of something*". In social and human sciences, value means the principles which a person or an organisation believes in and adheres to. A person or an organisation defines its value system that consists of core values such as reputation, innovation, ethics or knowledge sharing. In the product context, the X50-150 standard (AFNOR, 2014) defined value as "*a judgement made on a product by users on the basis of their expectations and motivations. More specifically, value increases when customer satisfaction increases or the incurred* *cost on product decreases*". Based on this definition, the value of a product is mathematically specified by Equation 2-2 (Yannou, 1999).

$$\text{Value} = \frac{\text{Adequacy degree of the product compared to the need}}{\text{Product cost}} \tag{2-2}$$

The final outcome (product or service) of a project is considered as the convergence of user and producer. For a user, this outcome is seen from the utility that it can bring to meet certain needs. However, a producer considers the outcome as the result of several actions to accomplish certain technical requirement. This double vision makes the concept of value become different depending on the point of view.

From the point of view of potential users, value is evaluated by comparing the use performance and the expenditure. The use performance is considered as the degree of satisfaction regarding the particular needs to be met. It is evaluated when the user receives the final outcome. The expenditure refers to all types of monetary expenses (for example, acquisition price and usage cost). It appears during the whole duration of utilisation. For example, the customer value can be described as "*the quality I get for the price I pay*" (Zeithaml, 1988). This evaluation refers to the use value as shown in Equation 2-3.

$$\text{Use value} = \frac{Use\ performance}{Expenditure} \tag{2-3}$$

For a producer that designs and realises the final outcome (product or service), the value is evaluated by comparing the functions and costs. The functions are the technical performance concerning the requirements and constraints. The costs are all the necessary spendings made to realise these functions. This evaluation describes the product value as shown in Equation 2-4.

$$\text{Product value} = \frac{Technical\ performance}{Cost} \tag{2-4}$$

However, both expressions can be formalised into a generic expression as shown in Equation 2-5.

$$Value = \frac{\Sigma(+)}{\Sigma(-)} = \frac{m_1b_1+m_2b_2+\cdots+m_nb_n}{n_1c_1+n_2c_2+\cdots n_mc_m} \tag{2-5}$$

Where m_i and n_j are magnitudes of given factors or criteria, b_i is a specific benefit and c_j is a specific cost.

This equation expresses that value evaluation is a subjective judgement made by the customers regarding the set of positive points (for examples, quality, advantage and satisfaction) and negative points (for examples, the price and time to obtain the result) of a particular project, product or service.

But neither of these definitions can correctly fit the context of the current research because the dimension of value is considered as a non-financial term in the proposed methodology. Therefore, value is defined as the measurement of a stakeholder satisfaction regarding the expectations. It is evaluated by the users and expressed by the appreciation level of a number of performance indicators on the results of the project. It should be noticed that the value definition is subjective and varies with the stakeholder points of view.

VALUE
Degree of satisfaction of a set of stakeholder expectations or needs, expressed by the appreciation level of a number of performance indicators.
Examples (for a PhD candidate in a doctoral programme): • Importance of the scientific contribution of the results • Quality of the thesis report and oral defence • Number of publications and communications accepted • Total duration to complete the whole thesis programme

Because value depends on the types of expectations or needs to be satisfied for a certain class of stakeholders, which is nearly unlimited, it can be defined in many various ways depending on its intended purpose and use. Therefore, there is no detailed classification that can be proposed at this stage of knowledge, except in a simplistic way according to classes such as: societal value, ecological value, economic value, technical value, scientific value, sentimental value, and so on.

Nevertheless, for the sake of the methodology proposed in this document, we can distinguish "*expected value*" from "*perceived value*". Expected value is the value that a stakeholder would like to get from a project, service or system. It is expressed through qualitative or quantitative descriptions of the predefined objectives. Perceived value is the real value that a stakeholder can finally get from a project, service or system. It is expressed through performance measurement on the final deliverable at the moment of evaluation. The degree of satisfaction is identified through the comparison of these two elements.

This clearly shows that the value of an artefact (project, service, system or product) not only depends on the stakeholder but also on the evaluation period. For instance, the value of a Ph.D. thesis will not be calculated in the same way from the point of view of the student, of the supervisor(s) and of the doctoral school (or academic institution). Furthermore, at the start of the doctoral work, if the topic is timely and concerns a hot research topic, the expected scientific value can be high while the real or perceived value can only be measured and assessed at the end of the work.

Interesting to note that in many cases, the expected value (for instance, from the point of view of a producer or a vendor) and the perceived value (for instance, from the point of view of a customer) are the bases for negotiation. Each party may have a fairly different view of the same artifact.

2.1.1.4 Concept of risk

ISO 31000 standard defines risk as "*effect of uncertainty on objectives*" (ISO 31000, 2009). This standard provides a generic definition and basic reference for risk management. While applied to different research contexts, this definition should be further detailed to be adapted to particular situations.

In the context of project management, risk is defined as the possibility that an event occurs and affects the achievement of some of the project objectives (for example, impacting the forecasted completion date, cost and specifications) (COSO, 2004). The occurrence of events comes from internal or external origins of the project (Rodney et al., 2015) and the consequences could be positive or negative on the progress of project activities (Gourc, 2006). Event occurrences can have their origins in vulnerabilities or deficiencies of the system being the subject of the project. When they occur, there is an impact (positive or negative) on the course of the project. In the current research work, the proposed definition of risk is:

RISK
Consequence of an event occurrence impacting the achievement of some of the different stakeholder objectives.
Examples (for a PhD candidate in a doctoral programme): • The scope and the key points of the research topic are ill-specified • The planning is inadequate and not efficiently controlled • Necessary resources (method, tool and equipment…) are not correctly defined or are unavailable • The student suddenly faces a long term disease and must stop the research work

To ease risk analysis, it is necessary to develop a classification of different types of risk. This classification can be used as a reference list and help the evaluator to identify all relevant elementary risks in a particular decision context.

The INCOSE Systems Engineering Handbook (INCOSE, 2004) defines four major types of risk: (1) technical risk (concerning technical problems regarding requirements, implementation, integration, performance, etc.), (2) cost risk (dealing with budget, planned resource, cost due to unexpected change, etc.), (3) schedule risk (regarding scheduled milestones, work breakdown, project accomplishment, etc.) and (4) programmatic risk (i.e. risk beyond the control of the project manager such as mission change, top level management decisions regarding project priority or external decisions of customers to delay or cancel requirements, orders or options).

To describe the relative risks at various levels of the company, Cleary & Malleret (2006) divided risks differently in four categories: strategic, financial, operational and project related risks. Regarding different aspects of a project or process, these categories can be further detailed as: (1) risks related to identification of needs, (2) technical risks related to the production of the product or service, (3) risks related to planning and scheduling, (4) financial risks, (5) risks related to communication between different systems, (6) risks related to resource acquisition, (7) risks related to environment constraints, (8) risks related to the security and (9) risks related to legislative constraints.

Based on these descriptions, a more detailed classification is proposed with respect to the different categories of project management processes (Figure 2-3). The detailed contents can be found in Appendix B.

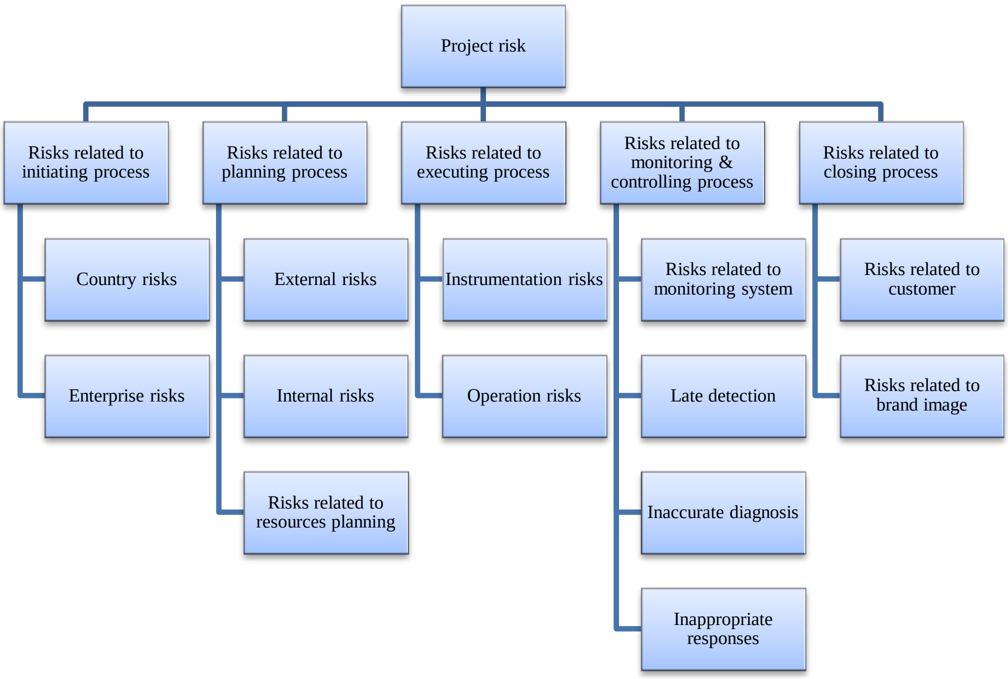


Figure 2-3. Risk classification by project management process type

Similarly to the proposition for the dimension of cost, the classification includes various types of risk that may be involved in different project contexts. In practice, the evaluator can use it as a check-list to develop the risk structure in a special decision context.

The concepts of benefit, cost, value and risk are widely used in different research fields and their definitions vary with the context of application. The objective of the analysis made in this section was to propose adapted definitions of the key concepts that define the research area for each basic dimension. Based on these definitions, the next step is to formalise the concepts and develop relevant conceptual models for the purpose of conceptualisation and evaluation.

2.1.2 Conceptual models of cost, value and risk

2.1.2.1 Context

The complete structure of the BCVR based performance evaluation methodology will be developed on the basis of individual conceptual models, one for each dimension. The objectives for driving the development of these models are: (1) description of the relations among the different key concepts used in each dimension for the purpose of evaluation and (2) establishment of a basis for software development in the future work to ease the evaluation process.

Remember that the concept of benefit has been defined as a non-monetary term and that benefits are expressed as literal expressions in the current approach. Therefore, the conceptual model development only focuses on the other three dimensions of cost, value and risk, which are quantitatively evaluated in the proposed methodology. A thorough analysis of these models is presented in this section.

UML (Unified Modelling Language) class diagrams (OMG, 2015) are commonly used by researchers to develop different conceptual models. This notation is used to present the conceptual models proposed in the methodology. The roots used for their elaboration have been based to a large extent on:

- For the axis of cost, the cost models described by Mauchand (2007), themselves based on the "Entité coût" methodology (H'Mida et al., 2001) and the MERM model (Manufacturing Engineering Reference Model) (Brinke, 2002).
- For the dimension of value, the conceptual model proposed to describe the modelling elements of value networks (Daaboul et al., 2014). In addition, the activity-based model (Vernadat et al., 2013) proposed for value and risk evaluation has also been considered.
- For the dimension of risk, the conceptual model developed at the CIRANO Centre (Bernard et al., 2002) as well as generic risk models proposed by Sienou (2009), who adapted these risk models in the form of UML class diagrams according to models from RBDM (Risk Based Decision Making) approach, COSO (Committee of Sponsoring Organisations of the Treadway Commission) organisation and OGC (Office of Government Commerce).

The aim of the conceptual models is to present the theoretical bases and the main elements for the concepts of cost, value and risk used in the methodology. Compared to existing models, some further improvements should be added. The reasons are:

- The existing models are mainly focused on presenting relations among different concepts, but few of them can be used to help the users in cost, value and risk assessment processes.
- The existing models are more about the internal structure of cost, value and risk. It means that the external terms, such as the decision context, are not fully studied and integrated in the conceptual models.
- The existing models can hardly fit the development of complicated systems. Therefore, the systems engineering approach should be considered for the elaboration of these models.

The following conceptual models of cost, value and risk are proposed to comply with these three aspects. For each of them, first the conceptual model itself is presented in the form of a UML class diagram and the definitions of relative concepts are given. At last, the example of the doctoral project is added to illustrate the proposed models.

In the current research, some hypotheses are applied to develop the individual conceptual models of cost, value and risk in the context of performance management and decision making.

- The overall cost, value and risk are measured based on the measure of elementary components for each dimension.

It is considered that each dimension contains a set of measurable elements that can be identified by a top-down analysis. Therefore, qualitative or quantitative measurements for each dimension are performed at the elementary level. Then, the elementary measures must be aggregated into an overall result for the purpose of decision support.

- Activity-centric models only partially fit the application areas of the current research.

Activity-centric models, such as Activity-Based Costing (Cooper & Kaplan, 1988) or activity based value-risk model (Shah, 2012), are constructed around the concept of activity. They can only be applied to the situations where the detailed information about the activities involved in the project is clearly identified. They do not fit well the case of evaluating the opportunity of a new project that usually does not have detailed information on the predefined activities. Therefore, the term of activity does not appear in the proposed conceptual models.

- The individual model of each dimension should be developed on the basis of a common logic.

It is supposed that the overall performance is quantitatively expressed by the separate estimation results of the overall cost, value and risk. Although the content and characteristic of each dimension are not the same, the measurement of each dimension should be done using a common structure in order to integrate measurements in different dimensions into the same methodological framework.

The proposed individual models include three main parts: (1) the main components of the conceptual model that are presented in terms of UML object classes, (2) the associations among the different components that are described by lines connecting two object classes and (3) the main methodological sequence steps that are marked by numeric numbers. The detailed descriptions of each model as well as the methodological steps are presented in the subsequent sections.

2.1.2.2 Conceptual model of cost

Based on the definition given in Section 2.1.1.2, a conceptual model of cost is proposed as shown in Figure 2-4.

Indeed, in an industrial project the global cost consists of a set of measureable elementary cost components that can be a function, an activity or an operation of the final result of the project or of a life cycle phase of the project. According to specific application contexts, these components can be further classified into different types (as shown in Appendix A) and different levels (strategic/tactic/operational). One component may still contain some sub-components if it cannot be directly measured by an estimation method.

A cost component is impacted by one or more cost drivers, which are inductors that influence the result of cost measurement. It can be an event, an operation or an object (human, material or information) involved during the life history of a project.

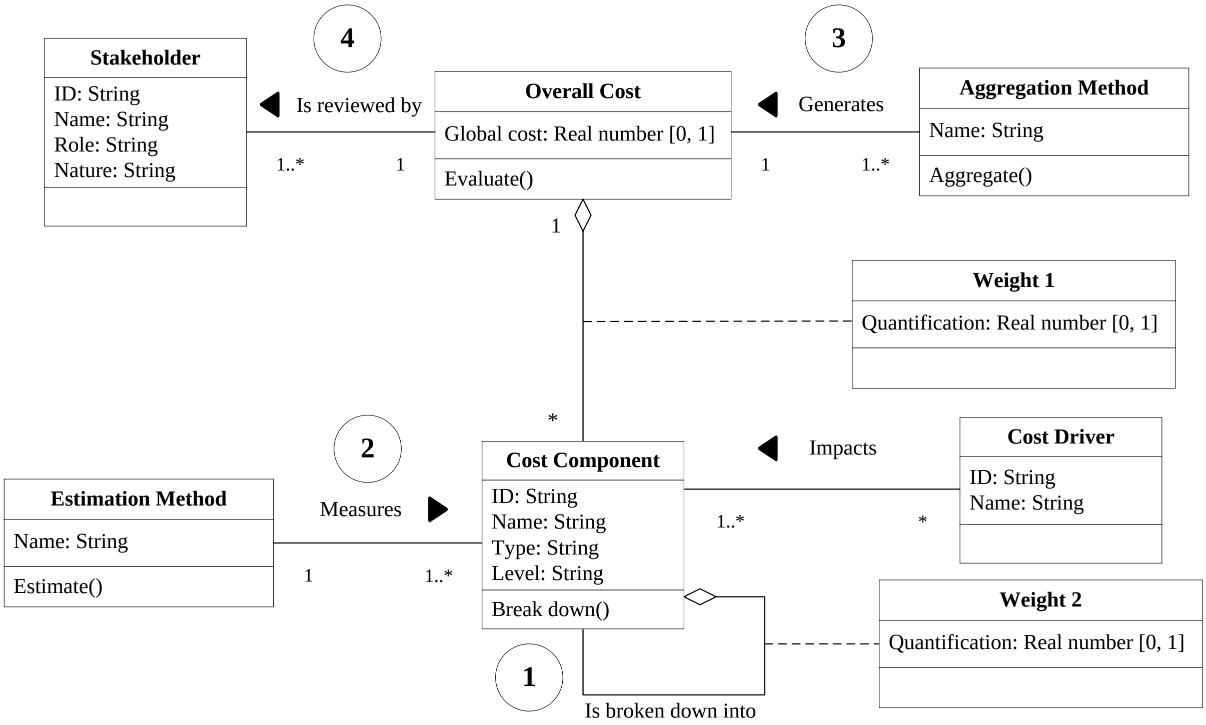


Figure 2-4. Conceptual model of cost

For the purpose of decision making, the elementary expressions of cost components should be aggregated into an overall result using a selected bottom-up aggregation method so that the stakeholder or decision maker can review the overall cost of the project. During the aggregation operation, the preference of the evaluator is reflected by the quantitative weight, which is a coefficient assigned to each basic element according to the evaluator preference. However, the weighting for each cost component may be less important because all the components or sub-components are objectively expressed by monetary terms.

The overall cost of a project will be normalised in the methodology into a real number between 0 and 1 to ease the final decision making on a normalised scale. It will be reviewed by at least one stakeholder holding a particular role (sponsor/project team member/customer/partner) and having a different nature (internal/external, supporter/neutral/resistor).

The numeric numbers in the cost model indicate that the project cost evaluation involves the following main operations: (1) identification of the hierarchical structure for the project cost, (2) cost assessment of cost components with selected estimation methods, (3) generation of the overall cost expression with adapted aggregation methods and quantitative weights and (4) cost evaluation based on the evaluator preferences.

Let us take the example of the doctoral thesis. If the cost of the doctoral project is evaluated by the doctoral candidate (stakeholder), it can be considered that “living expenses” is a major component of the overall cost. This cost can be further decomposed into different measurable sub-components (for examples, accommodation, transportation, food…) to execute the quantitative measurement. The sub-component "accommodation" covers cost entities such as "room in the student residence (material)", "administration (human and information)" and "water and electricity (energy)". They can be measured by monetary criteria such as "monthly rent", "administrative fees" and "utilities". However, if a piece of equipment in the room is damaged (cost driver) by the tenant, it may cause additional fees in the rent. Based on the sum (aggregation method) of the measurement results of the three subcomponents (if they have the same importance), the qualitative expression for the component "accommodation" can easily be obtained (in this case, it is the cumulative sum).

Obviously, the overall cost of making the thesis will be computed differently from the point of view of the university or engineering school hosting the student for the Ph.D. programme (other stakeholders). In this case, it includes the part of the salaries of the supervising professors, the overhead costs (office, telephone, etc.) and the cost of travels (trainings, seminars, conference fees, mission expenses, etc.) for instance. The cost structure to be used in the evaluation is specific to each stakeholder.

2.1.2.3 Conceptual model of value

Based on the definition given in Section 2.1.1.3, the proposed conceptual model of value is depicted as shown in Figure 2-5.

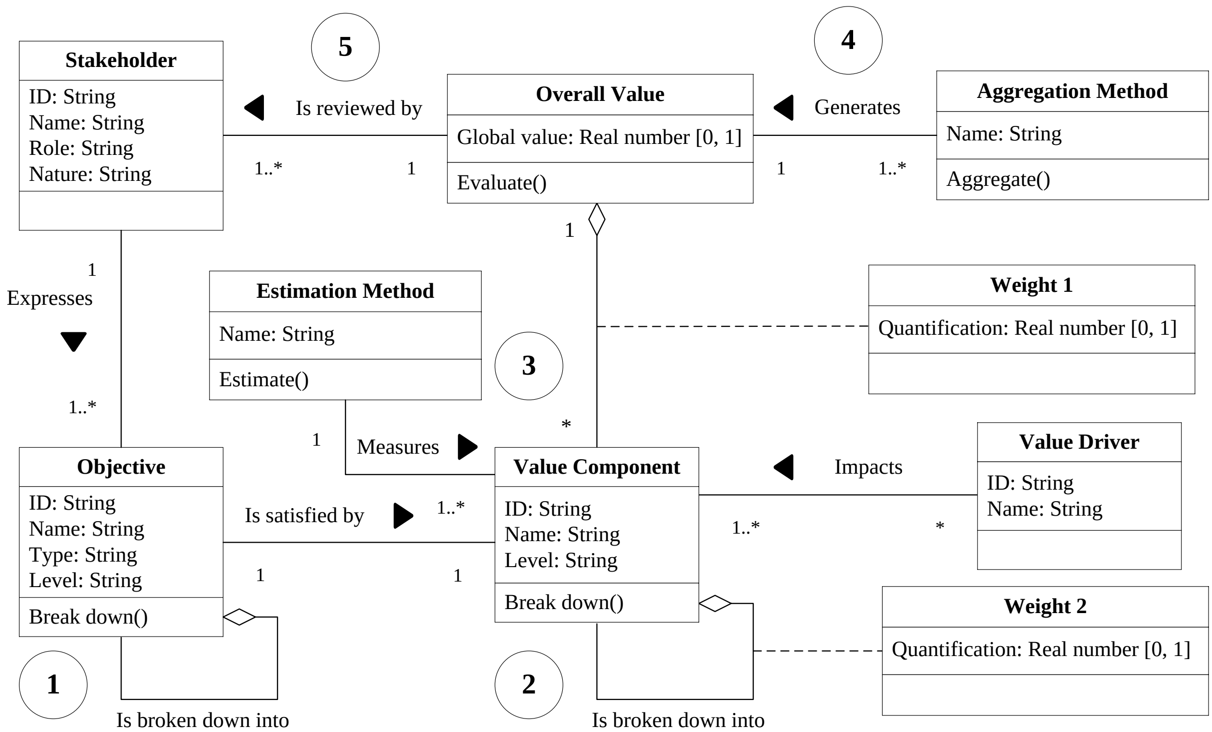


Figure 2-5. Conceptual model of value

The involved stakeholders have specific expectations based on their needs in the project. Each expectation is expressed by an objective, which is a goal that a stakeholder intends to achieve at the end of the project. The objective is also the clarification of the stakeholder needs by means of formal languages, but only the textual description is selected in the current research. An objective has a specific type (strategic, fundamental or means objectives) and level (strategic, tactic or operational). Therefore, a hierarchical structure can be developed based on the modelling of different objectives.

The overall value contains a set of value components. Like the cost components, the value components also have different levels with the basic level that can be directly measured through preselected estimation methods. Because value is created by satisfying the objectives of stakeholders, it is considered that elementary objectives are associated with elementary values. So, the hierarchical structure of project value can be developed based on the corresponding breakdown structure of objectives

Each value component may be influenced by several value drivers, which are events or objects that have impact on the creation of elementary value. Then, these elementary quantitative value expressions are aggregated by means of selected aggregation methods and quantitative weights to generate the overall value. It is then normalised into a real number between 0 and 1 to make easier the final decision making. The overall value will also be evaluated by the project or system stakeholders for a specific decision problem.

The numeric numbers in the value model indicates the following main operations in value estimation: (1) objective modelling regarding the specific decision context, (2) identification of the top-down structure for the project value, (3) value assessment with selected estimation methods, (4) generation of the overall value with adapted aggregation methods and quantitative weights and (5) value evaluation based on the evaluator preferences.

In a doctoral project, the fundamental objective of the doctoral candidate is to be successful in the project to get the Ph.D. diploma. This global objective can be further specialised by some sub-objectives, such as “finish the project within the duration predefined by the doctoral school”, “realise the work with sufficient quality”, “propose innovation in the research field” and “have sufficient scientific publications”. Therefore, it can be considered that the overall value of the project consists of four components, which are “thesis duration”, “thesis quality”, “innovation” and “publication”. However, if the doctoral candidate uses inadequate methods or tools to develop the research results (this event is considered as a value driver), it will lead to additional time to adjust the work, insufficient quality of the final result and poor innovation of the research. This means that the value of the components “duration”, “quality” and “innovation” will be negatively influenced.

However, the value structure is not the same for another point of view. For the doctoral school of the Ph.D. project, the fundamental objective is to control that the Ph.D. candidate fulfils the conditions to get the Ph.D. diploma. This objective can be further detailed by some more specific objectives, such as “ensure the Ph.D. candidate can finish the project within an acceptable time period”, “improve the quality of the Ph.D. programme” and “improve the research competence of the institute”. Therefore, the value components are “thesis duration”, “programme quality” and “research competence”.

2.1.2.4 Conceptual model of risk

The conceptual model of risk has been developed by following the same principles as for cost and value. Figure 2-6 presents the proposed conceptual model of risk with different elements and their interactions.

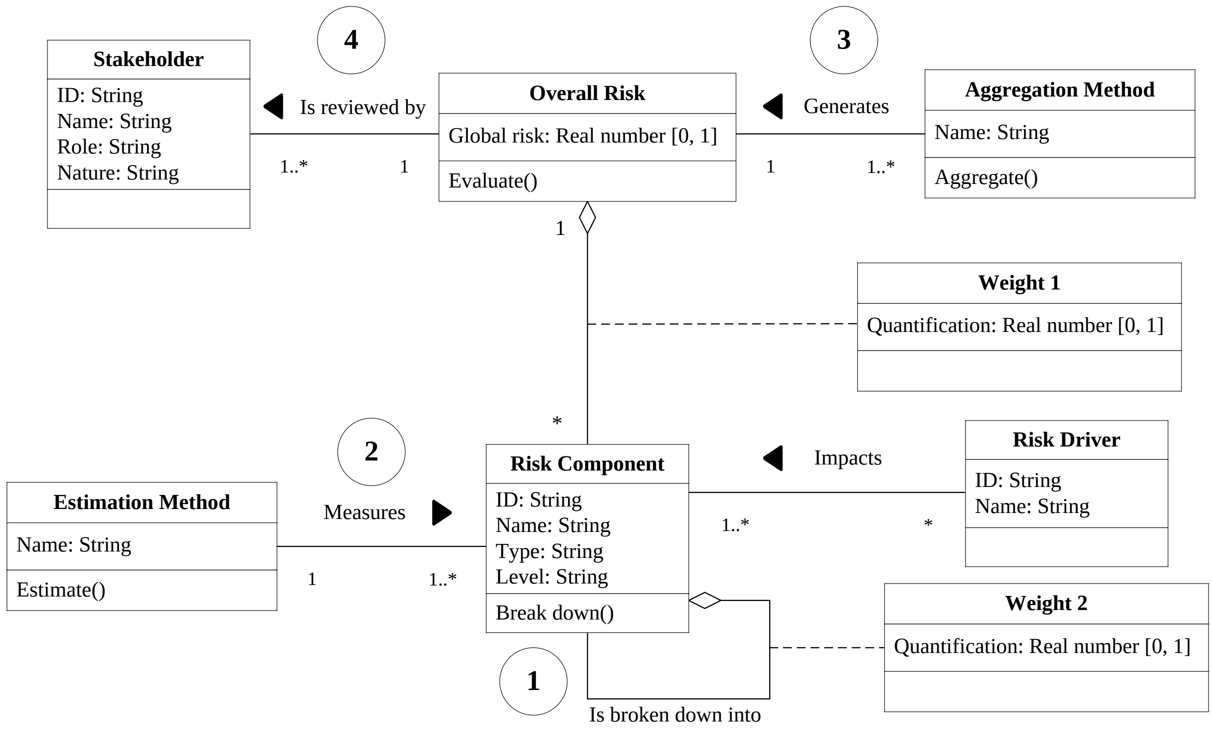


Figure 2-6. Conceptual model of risk

The global project risk can be detailed by a set of risk components that are related to elementary risk expressions. These components can be further classified into different types (as described in Appendix B) and different levels. A risk component can also be expressed by several sub-components at the lower level for the purpose of risk assessment. A risk component is impacted by several risk drivers that influence the result of risk measurement. The detailed description of a risk component will be presented in the following section. The elementary expressions of risk components should be aggregated into an overall result by using a selected bottom-up aggregation method in order to help the stakeholder in making a risk evaluation. The overall expression should also be normalised into a real number between 0 and 1 to make easier the decision making on a normalised scale.

The numeric number indicates that the risk model possesses similar operations than the cost model. They are: (1) identification of the risk structure regarding the project context, (2) risk assessment with selected estimation methods, (3) generation of the overall risk expression with adapted aggregation methods and quantitative weights and (4) risk evaluation based on the evaluator preferences.

In a Ph.D. project, the overall risk can be defined as “failure to obtain the Ph.D. diploma” which can be further expressed by sub-components such as “time delay”, “insufficient quality of research” and “termination of the funding for the Ph.D. programme”.

Besides the selection of estimation methods, these results are also influenced by the risk drivers that can be defined as “variables that cause the occurrence of some events that lead to the impacts on certain parts or the whole project/process”. Figure 2-7 presents the elements and their relations modelling the concept of risk drivers and agents involved to complete the conceptual model of risk.

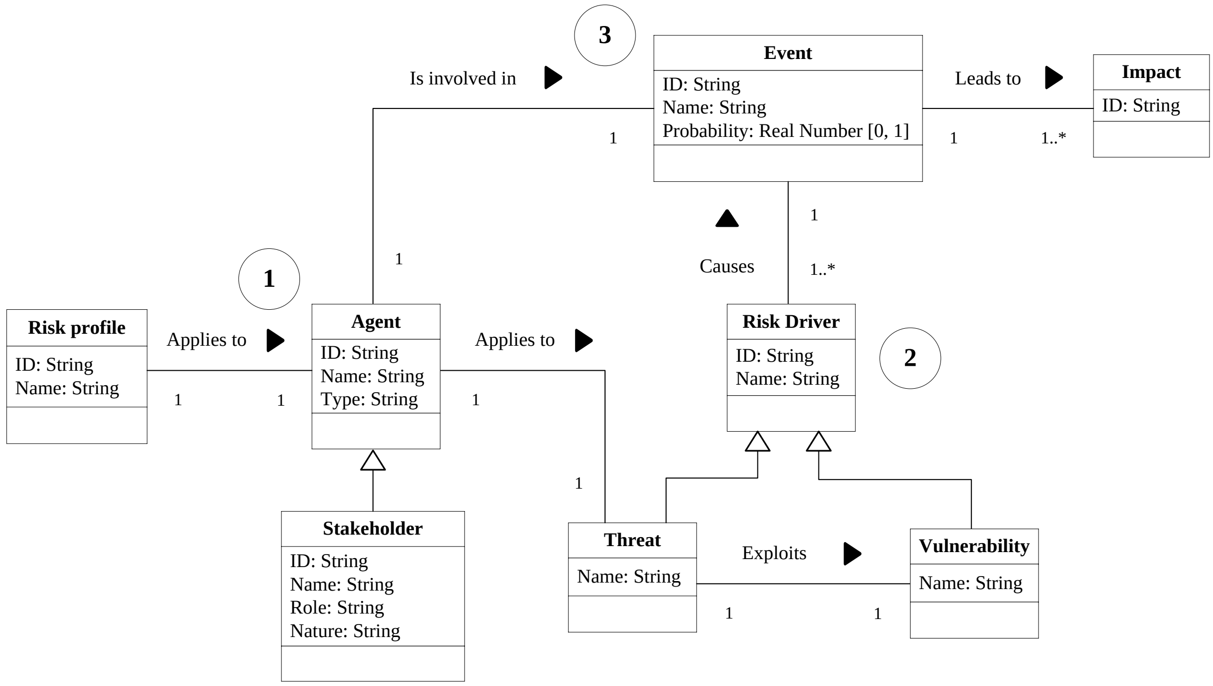


Figure 2-7. Conceptual model of risk driver

Risk drivers cause events that lead to a range of negative or positive impacts in a project. The event has a characteristic of potentiality that can be described by its probability, which represents the chance of occurrence expressed as a number between 0 and 1 (higher number means higher chance and 1 is absolute certainly). The associated impact (consequence) can be quantitatively assessed by its gravity.

A risk driver can be a threat or vulnerability. The former is the potential danger in likelihood to a risk source that can lead to an event with a consequence. The latter is the intrinsic properties of something resulting in likelihood to a risk source that can also cause an event.

There are different agents that can be involved in an event. In the proposed conceptual model, the concept of agent can be split into three categories: human, technical and environmental agents. The former category refers to persons or human beings involved in the project or system. The second category refers to active objects (material or informational) that have interactions with the project or system. The latter category refers to environmental entities or conditions such as weather, temperature, pressure, day or night conditions, etc.

Each agent has a risk profile that describes all the relative characteristics that may cause risk by the agent. The stakeholder of a project can be considered as a specific kind of agent that not only affects the project but can also be affected by the results of the project. It therefore appears as a model entity of its own.

For the analysis of risk drivers in a particular decision context, the numeric numbers in this model indicates the following main operations: (1) identification of main risk agents, (2) identification of the main threats or vulnerabilities that are related to the risk agents and (3) list of events that may be caused by the identified risk drivers.

For example, in an urban transportation system, the human agents are the driver, the passengers, the traffic engineer and the management authority, while the technical agents are the vehicle, the road and the information system. Finally, environmental agents refer to surrounding or environmental conditions such as temperature, weather conditions, pressure, etc. For instance, for the urban transportation system, the risk of operation failure increases when there is ice or snow in winter. These risk agents cause threats such as poor weather conditions for driving (related to environmental agents), infrastructure problems (related to technical agents) and bad driving attitude (related to human agents). These threats may cause events such as road accidents that could lead to property and other types of losses (for instance, loss of life).

These individual models show that each dimension is directly measured at the elementary levels to get quantitative expressions for the purpose of performance management and then these elementary expressions can be aggregated into one global result per dimension to support the decision making process of the evaluator.

Each axis presents one individual aspect of the overall performance. These individual conceptual models can be integrated into a global structure for the purpose of comprehensive performance evaluation. The next section presents the aggregated model.

2.1.2.5 Integrated conceptual model

As already explained, in the current research the overall performance of an industrial project or system is quantitatively expressed by three dimensions: cost, value and/or risk. It is considered that these three dimensions are orthogonal at the global level. It means the overall cost, value and risk cannot be further aggregated into one global expression to represent the overall performance.

However, some common factors (for example, time, quality or availability) can simultaneously influence the elementary estimation results of more than one dimension, even if they will be carried out by different objects. So, these axes can have interactions at the elementary levels. They are said to be orthogonal at the upper level of aggregation in the sense that (1) the global value of the indicator is computed along a single axis and (2) the three global indicators obtained can be interpreted on their own and be taken separately into account in the decision making process.

Based on these observations, the proposed integrated model of cost, value and risk for performance management and decision support is shown in Figure 2-8.

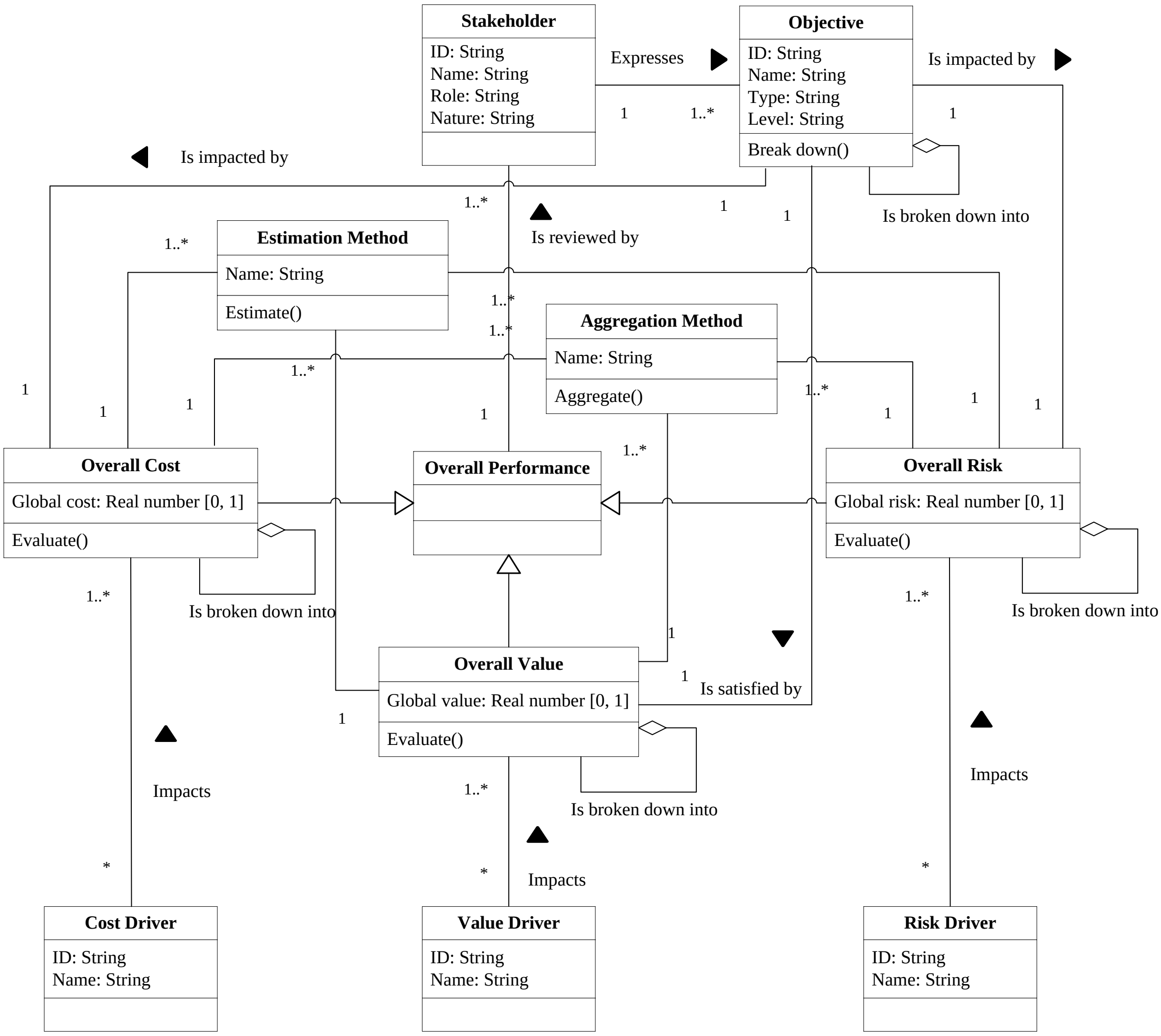


Figure 2-8. Integrated model of cost value and risk for performance management and decision support

For the sake of performance management, each dimension is decomposed from top to bottom in order to obtain measurable elements. To limit the complexity of the analysis, these breakdown structures should be developed by following a common basis. In most cases, including opportunity evaluation for a new project or monitoring an ongoing project, this common basis can be the hierarchical structure of objectives that are expressed by stakeholders. In addition, the main activities in a project or process can also be used as another common basis if they can be identified in a specific decision problem. Each of these elements is qualitatively or quantitatively estimated by a selected estimation method and then these measurement results are quantified for further analysis and aggregation. These results are impacted by two main aspects: selected estimation methods and interactive cost/value/risk drivers.

For the sake of decision support, the quantitative elementary expressions should be integrated into one global result per dimension to make easy the comparison among several project alternatives. Except the dimension of cost, which is usually fully expressed by quantitative monetary terms, the elementary value and risk are not measured with the same unit. In addition, the elementary expressions contain a mix of quantitative and qualitative measures. To generate the aggregation operation, it is necessary to transfer all quantitative results into quantitative expressions, preferably between 0 and 1. Then, an aggregation method is selected to generate the individual overall expression for each dimension.

The proposed definitions and conceptual models presented in this section complete the research on the key concepts of benefit, cost, value and risk. Based on the conceptual models, the main operations in performance evaluation can be identified as the basis for the methodological framework. However, besides the multiple aspects of the four selected dimensions, the evaluation methodology should also meet other characteristics of performance. Therefore, an analytical framework for performance expression is developed in the following section.

2.2 Analytical framework for performance expression

It is considered that the concept of industrial performance is multidimensional and relative in nature (see Section 1.3.1.3). The performance of an industrial project should be assessed from multi-viewpoint, multi-level and multi-criteria. In addition, a performance expression depends on the objective to be met. It is also influenced by the time, the way and the condition under which it is measured and interpreted. In this context, the proposed performance evaluation framework should meet these characteristics in order to increase the reliability of the final performance evaluation results for the purpose of decision support.

2.2.1 Performance expression framework

From a generic level, we claim that the performance of an industrial system must be comprehensively identified from three necessary perspectives, namely *stakeholders*, *evaluation periods* and *evaluation variables*. This statement is summarised by Equation 2-6.

$$\mathrm{P} = (\mathrm{S}, \mathrm{T}, \mathrm{V}) \tag{2-6}$$

Where, P is the overall performance of an industrial system or project; S is a set of points of view from selected stakeholders in the evaluation; T is the time period over which the performance evaluation is executed (it can be an instant, a life cycle phase or the whole period of the project) and V is the set of evaluation variables to be considered. As stated as the fundamental claim of this thesis, it is supposed that the performance of an industrial system can be comprehensively expressed by the following four dimensions: benefit, cost, value and risk. So, it is assumed that these evaluation variables can be categorised along these four dimensions.

However, it may happen that in some particular cases, some elements, which normally fall within one of these four categories, must be considered as extremely important and as a dimension of its own for the project success (for example, delay is an essential evaluation element for fashion design projects). Therefore, the set of basic evaluation dimensions can be adapted to the particular context of the project to include such an additional dimension of its own, if necessary. Figure 2-9 presents the global structure of the proposed framework applied to the generic project management context.

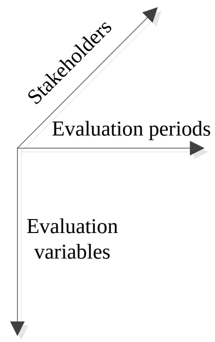


Figure 2-9. Analytical framework for performance expression

The proposed framework includes a set of basic elements within each of the three independent perspectives, which are: stakeholders, evaluation periods and evaluation variables. Each basic element represents the performance of one evaluation variable at one evaluation period along the project life history from one stakeholder point of view. Based on the particular context of the decision problem, the evaluator selects the performance components (relevant stakeholders, specific time periods and main evaluation variables) to define the scope of the performance evaluation problem. Figure 2-10 presents an example of the proposed framework applied to the generic project management context.

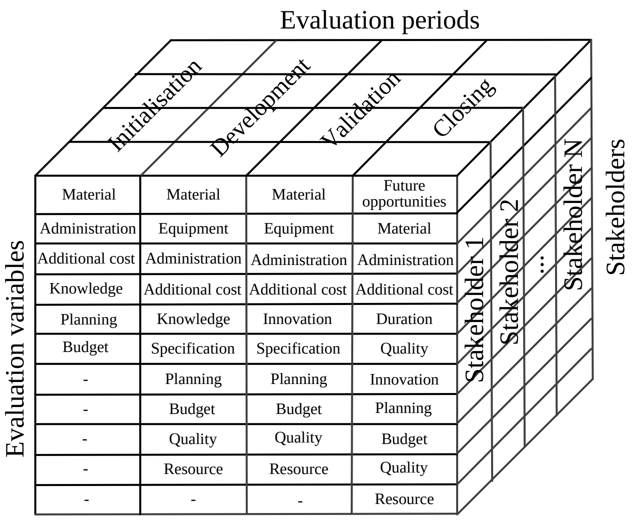


Figure 2-10. Performance expression framework (for the project management context)

The proposed framework for performance expression has the following advantages:

- Cope with the multidimensional and relative characteristics of industrial performance

Altogether, the perspectives cover the particular characteristics of industrial performance. The first perspective (stakeholders) satisfies the aspects of multi-viewpoint; the second one (evaluation period) makes it possible to perform measurement and assessment of performance on different time intervals of the project or system life history; and the third one (evaluation variables) satisfies the multi-level and multi-criteria requirements. Therefore, this framework can comprehensively cope with the performance evaluation of an industrial project.

- Propose a flexible structure that can be adapted to the particular decision context

The detailed components of performance vary with the particular decision context and the evaluator preferences. For instance, someone may prefer to focus on the overall performance of one specific time interval during the project or system life (Figure 2-11); others may prefer to highlight one particular evaluation variable during the whole project or system life history (Figure 2-12). The proposed framework allows the evaluator to easily combine different elements in order to build up the relative structure of the performance appraisal to face different situations.

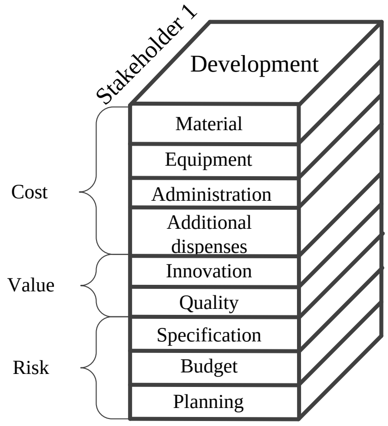


Figure 2-11. Overall performance definition of a project development phase

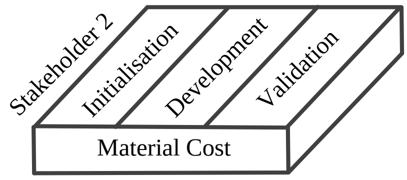


Figure 2-12. Project total material cost

The purpose of this performance evaluation framework is to help analysts or decision makers to organise their particular performance evaluation environment by identifying all relevant stakeholders, defining when to make evaluations and specifying all variables to be taken into account in the performance equations of each evaluation period for assessing cost, value and risk of the industrial project or system. To better explain how it works, each perspective needs to be described in turn in more details.

2.2.2 Performance perspectives

The detailed description of each perspective is presented in the following sub-sections. A simple illustration of the performance evaluation of a Ph.D. thesis programme is also given to ease the understanding of the proposed approach.

2.2.2.1 Stakeholder identification

The main objective of a project or system is to generate consistent results to satisfy the stakeholder needs or expectations, firstly the project or system owner. It is therefore critical for project success to identify all the involved stakeholders in the early phase of the project to analyse their interests, needs and expectations, as well as their relative importance and influence.

Large and complex projects will have a huge number of stakeholders that are different in size, type and complexity. These stakeholders should be classified based on their interest, influence and involvement in the project in order to help the evaluator/analyst to focus on the necessary relationships to ensure the success of the project.

Stakeholder identification is a process, the aim of which is to identify the individuals or organisations that can impact or be impacted by a decision, activity or outcome of the project (or system). It also includes the analysis on their interests, interactions and potential impact on the project success. Figure 2-13 provides an overview of the project stakeholder identification phase.

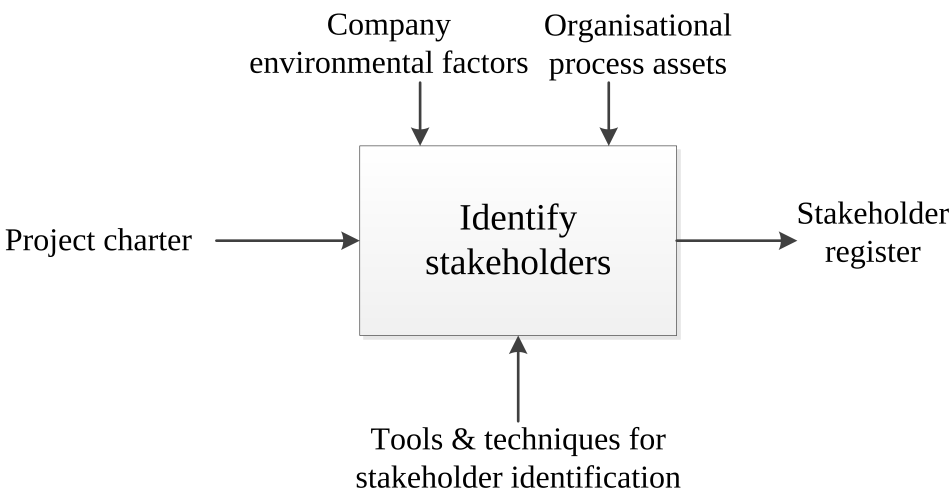


Figure 2-13. Overview of project stakeholder identification

The input of the project stakeholder identification phase is the project charter (or vision document of the project), which is used to present the high-level description of the result of the project. For a system, it can be a structured analysis of the system (for instance, SADT or IDEF0 analysis). It can provide information about external and internal partners related to the project as well as impact by the result of the project, such as project sponsor, customers, project team members and other individuals or organisations affected by the project. Based on this, the detailed requirements can be developed.

The enterprise environmental factors and the organisational process assets are two concepts proposed by the Project Management Institute (PMBOK® Guide, 2013) that can be used to complete stakeholder identification. The former refers to conditions, not under the control of the project team, that positively or negatively influence or constrain the project and its outcome. Some important external factors could be: government and industry standards, regulations, market conditions, infrastructure and external political conditions. Some main internal factors could be: organisational culture and structure, internal political conditions and available resources. The latter are the formal and informal plans, processes, policies, procedures and knowledge bases, specific to and used by the performing organisation. They can be divided into two categories: (1) processes and procedures for conducting work (for example, policies, standard template and general guidelines) and (2) corporate knowledge bases for storing and retrieving information (for example, past project files and historical information).

The tools and techniques for stakeholder identification include stakeholder analysis, expert judgment and meetings with end users. Stakeholder analysis is a technique to gather and analyse quantitative and qualitative information in order to determine interests, expectations and influence of stakeholders and stakeholder relationships (with the project and with other stakeholders). Expert judgment is judgment and expertise from groups or individuals (for examples, senior management, other units within the organisation, project managers or industry groups and consultants) to ensure comprehensive identification and listing of stakeholders. Project meetings are used to exchange and analyse information about roles, interests, knowledge of major stakeholders involved in the project.

As an output of the stakeholder identification, the stakeholder register is another term proposed by the Project Management Institute (PMBOK® Guide, 2013). It is used to identify stakeholders who can provide information on the requirements. This document contains all detailed information related to the identified stakeholders, including identification information (stakeholder contact information and its role in the project), assessment information (stakeholder major requirements, main expectations and potential influence for the project) and stakeholder classification (for example, internal/external, supporter/neutral/resistor).

For the example of the Ph.D. programme, relevant stakeholders are: the doctoral candidate, the supervisors (could be one or many), the doctoral school or administrative entity delivering the diploma, the institution hosting the student (university, research laboratory or engineering school) and the sponsor if any (one or more organisations financially supporting the research work).

In the current research, the change of stakeholders in different project life cycle phases is not taken into consideration. However, it should be noticed that the stakeholder identification phase should be developed and updated on a regular basis, because stakeholders may change along the life history of the project or system.

2.2.2.2 Evaluation periods

In the proposed performance evaluation framework, the main project or system life cycle phases are assumed to be the natural basic time periods over which performance of an industrial project or system needs to be measured and assessed. However, the definition of these evaluation periods is left to the responsibility of the analysts or the decision makers because they are the only ones who really know the relevant points in time when performance must be assessed and why.

In project management, although projects vary in size and complexity, all projects can be mapped to the following generic life cycle phases: (1) starting the project, (2) organising and preparing project steps or phases, (3) carrying out the project work and (4) closing the project. Then, depending on the particular context, the analyst or evaluator can adapt these life cycle phases.

Having selected the relevant life cycle phases (all or part) for the project at hand, the evaluator can identify the main activities for each step. This can help the evaluator to associate major elementary cost, value and risk elements with different life cycle phases for further performance measurement. While evaluating the opportunity of a new project, the evaluator may only focus on the starting phase during the performance evaluation. This means that the evaluation period perspective has one single phase in this case. But if this framework is applied to monitoring and control of an industrial project, it is important to identify the adapted project life cycle phases along the whole life history in order to repeatedly execute performance evaluation during the whole project life period.

For instance, in most of the cases, the elapsed period of a Ph.D. programme varies from 3 to 5 years. The normal duration is 3 years. The life history of a Ph.D. programme can be divided into different phases: initialisation, training, development, validation and closing. Figure 2-14 presents the main tasks in each life cycle phase of a Ph.D. programme.

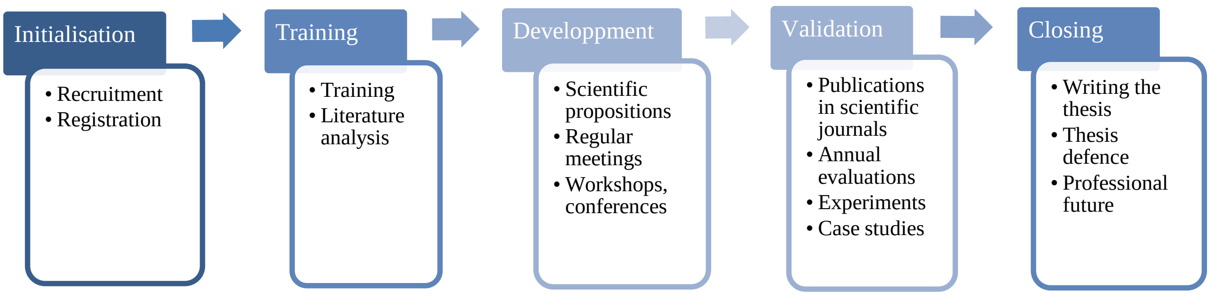


Figure 2-14. Life cycle phases of a Ph.D. programme

2.2.2.3 Performance evaluation variables

The perspective of performance evaluation variables identifies the elements that are directly related to or will be involved in the performance measurement. It consists of three facets: performance dimensions, performance variables and evaluation criteria. The relations among these concepts are shown in Figure 2-15.

The performance dimension facet forms the highest level in this hierarchical structure. It represents the basic axis on which the overall performance of an industrial project or system will be evaluated. In the current framework, overall performance is comprehensively evaluated by four independent dimensions:

benefit, cost, value and risk (but only the last three can be numerically rated). However, depending on the particular project or system context and depending on the decision maker preferences, other aspects (for instance, time) can also be added as a performance dimension.

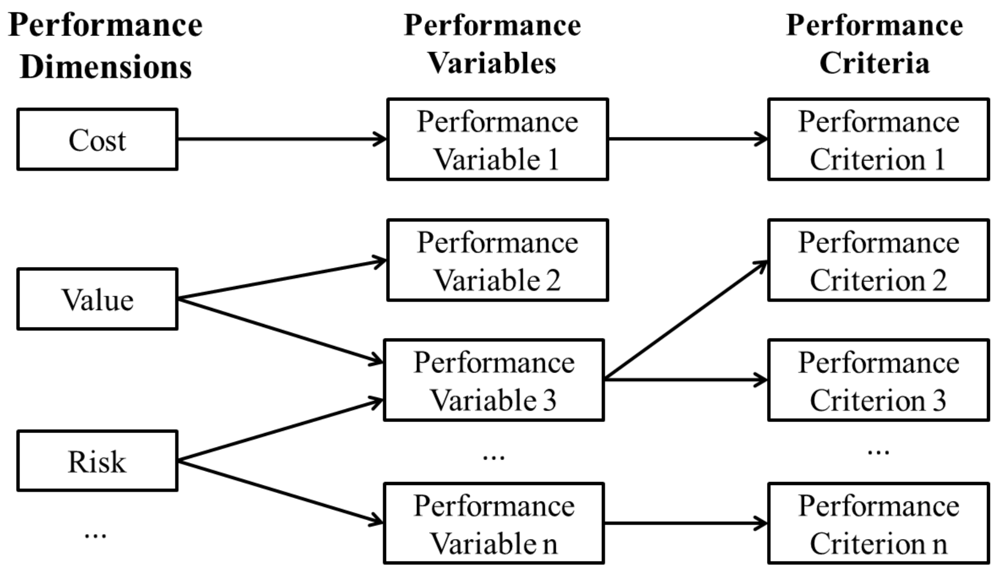


Figure 2-15. Relations between performance dimensions, variables and criteria

For almost all cases, one performance dimension cannot always be directly evaluated. Each dimension contains a set of elements that are commonly utilised as elementary measures within organisations to evaluate the performance. Therefore, performance variables are identified to represent the components of the performance dimensions. Each performance dimension is evaluated through one or several evaluation variables. Besides, these variables do not have the same level during the evaluation. It means that the relations among different variables can be described by a hierarchical structure. So, a breakdown analysis should be performed in order to express all the evaluation variables.

In this work, it is considered that the different performance variables do not interact. However, one variable can be simultaneously categorised into more than one dimension. For example, project delay could lead to additional expenditure and negative impact on the final project result. So, the variable “project duration” can be utilised both in the dimensions of cost and risk.

In many cases, a performance variable cannot be directly measured. Therefore, performance criteria should be identified in order to express each variable into a criterion that can be qualitatively or quantitatively measured. Although different performance variables are independent, they may have common criteria. For example, the time to finish the thesis project is applied to measure the elementary value “duration to finish the Ph.D. project” and the elementary cost “living expenses” that corresponds to all necessary spendings for daily life of the Ph.D. student.

Regarding the doctoral programme, there exist different external and internal evaluations to assess the performance from different points of view. For example, the French organisation HCERES *(le Haut*

Conseil de l'Evaluation de la Recherche et de l'Enseignement Supérieur) evaluates the performance of each doctoral school every four years. A doctoral school sets some rules to evaluate the performance of a doctoral candidate during a doctoral programme. In addition, different stakeholders may not have the same interest in a thesis project. Even if they have some common points of interest, the degrees of importance are also not identical for each of them.

For the thesis programme, we already mentioned that the main stakeholders are: doctoral candidate, supervisors, doctoral school and sponsor. Let us consider the point of view of the doctoral candidate as the selected stakeholder to express the representative evaluation elements in the different phases of a doctoral programme life history. The detailed information is presented in Table 2-2. It provides the analyst or evaluator with two kinds of information: the main variables that could be applied to evaluate the performance and the involved evaluation periods for each variable.

Based on this analysis, a performance evaluation structure can be deployed for a phase-based measurement, as shown in Figure 2-16. Then, the evaluation criteria should be selected to qualitatively or quantitatively express these performance variables. For example, for the evaluation variable "publication", the selected evaluation criteria could be: (1) number of publications, (2) type of publications and (3) scientific level of publications.

Evaluation periods

Evaluation variables

Initialisation	Training	Development	Validation	Closing
Living stipend	Skills development	Skills development	Skills development	Potential opportunities
International airfare	Living expenses	Living expenses	Living expenses	Living expenses
Material	Material	Material	Material	International airfare
Administration	Equipment	Equipment	Equipment	Material
Additional cost	Training	Scientific communication	Scientific communication	Administration
Knowledge	Administration	Administration	Administration	Additional cost
Planning	Additional cost	Additional cost	Additional cost	Duration
Budget	Knowledge	Innovation	Innovation	Quality
-	Specification	Publication	Publication	Innovation
-	Planning	Specification	Specification	Publication
-	Budget	Planning	Planning	Planning
-	-	Budget	Budget	Budget
-	-	Quality	Quality	Quality
-	-	Resource	Resource	Resource

Figure 2-16. Performance expression of a doctoral programme

The proposed performance expression structure provides the analyst/evaluator with all the necessary elements to express the overall performance of a specific project (respectively, system). The major advantage is that this framework reflects the multidimensional and relative characteristics of industrial performance. Based on this framework, the evaluator can obtain the performance evaluation results through the proposed evaluation process (see next section), which contains a set of methods and tools for performance management and decision support.

Table 2-2. Performance evaluation variables in each life cycle phase of a thesis project

Dimensions	Variables	Description	Initialisation	Training	Development	Validation	Closing
Benefit	Skills development	Improvement or acquisition of scientific skills and other capacities		√	√	√	√
	Potential opportunities	Potential opportunities for professional future					√
Cost	Living expenses	All necessary spendings related to daily life	√	√	√	√	√
	International airfare	Cost of one international round trip flight	√				√
	Material	All necessary spendings on office, energy, stationery…	√	√	√	√	√
	Equipment	All necessary spendings on computer, software and machines…		√	√	√	
	Training	Spendings on transports, tuition…		√			
	Scientific communication	Spendings on participation in scientific workshops, conferences…			√	√	
	Administration	All spendings related to school administration (registration, thesis defence…)	√	√	√	√	√
	Additional cost	Additional spendings on emergency events (illness, accident…)	√	√	√	√	√
Value	Duration	Total duration to finish the whole thesis programme					√
	Quality 1	Quality of the thesis report and oral defence					√
	Innovation	Scientific contribution of the results			√	√	√
	Publication	Number, type and level of the scientific publications during the programme			√	√	√
Risk	Knowledge	Insufficient knowledge on the research subject or underlying fundamentals	√	√	√		
	Specification	The scope and the key points of the research are not precise enough		√	√	√	
	Planning	The plan is not efficiently prepared and controlled	√	√	√	√	√
	Budget	Budget overrun regarding to estimation	√	√	√	√	√
	Quality 2	Insufficient quality of publications, thesis report and final defence			√	√	√
	Resource	The necessary resources (method, tool and equipment…) are not correctly defined or unavailable		√	√	√	√

2.3 Global structure of the BCVR based performance evaluation method

Although different methods and tools have been developed for performance management and decision support in industrial projects, there is still room for improvement in the development of an accurate and operational methodological approach that will guide the performance management analyst/evaluator in choosing and employing the appropriate methods and tools that can be adapted to his/her particular decision context.

The proposed benefit-cost-value-risk (BCVR) based performance evaluation method is a set of tools and techniques that not only guides the evaluator to measure and assess performance in a well-defined context, but also leads the measurement and management process towards objective achievement. Based on the BCVR analysis, the evaluator or the decision maker can perform opportunity evaluation for a new project or control execution of an ongoing project.

2.3.1 Basic assumptions

In this research work, some basic assumptions have been made in the development of the proposed methodology.

Firstly, the methodology can be applied in a multidimensional context. The proposed performance evaluation process is developed based on the proposed analytical framework for performance expression presented in Section 2.2. Therefore, the evaluation results issued from this approach can both integrate satisfaction of multiple stakeholder objectives and performance measurement with multi-evaluation variables at different decision levels and time horizons.

Secondly, it is reminded that the four performance dimensions (benefit, cost, value and risk) are considered independent at the overall level. Except the axis of benefit, which is only qualitatively analysed in the current research, the global quantitative expression computed for each dimension does not depend on elementary measures of the other axes.

Finally, it is considered that the overall (or global) cost, value and risk of an industrial project or system can hardly or seldom be directly measured. They are obtained from measurable elementary elements hierarchically organised through a common basis, which could be "objective-based" or "activity-based". Then, the elementary measurements must be aggregated into a global expression for the purpose of decision making or decision support.

2.3.2 Performance evaluation process

The objective of the proposed performance evaluation method is to comprehensively evaluate the overall performance of a new or ongoing industrial project based on qualitative and quantitative expressions of four essential (but not necessarily sufficient) dimensions: benefit, cost, value and risk. To get a better understanding of the method, the idea is to be able to process the performance management problem by means of a certain number of activities and processes. For this purpose, the aim of this section is to present the global structure of the proposed methodological approach, which consists of four main phases: *identification*, *quantification*, *aggregation* and *decision support*. They make up the performance evaluation process for decision making, as shown in Figure 2-17.

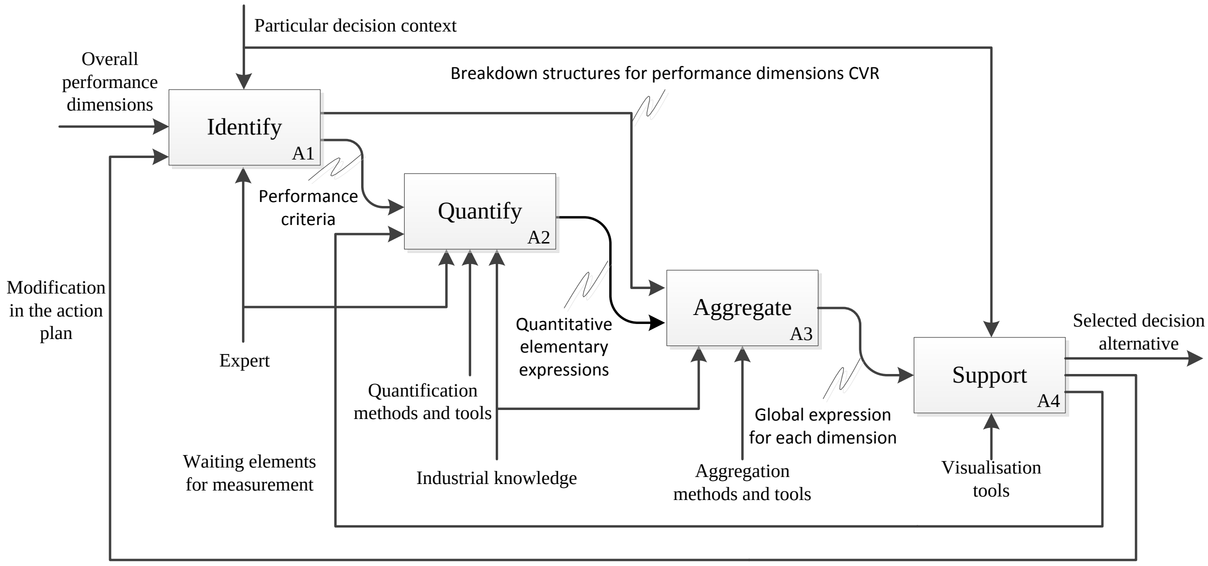


Figure 2-17. Global structure of the proposed performance evaluation methodology

These main phases are sustained by the individual conceptual models of the performance dimensions (as introduced in Section 2.1.2). Each step provides deliverables that are further analysed in the following phases. Through this four-step process, the overall performance expressions for all decision alternatives are generated. According to the final performance evaluations, the decision maker chooses the most preferred decision alternative or returns to the previous steps in the process to generate new evaluation results. The descriptions of each phase follow.

2.3.2.1 Identification

The first phase is the start-up phase of the proposed evaluation methodology. It deals with the identification of all relevant aspects in each performance perspective to express the overall performance regarding the particular decision context, as well as the identification of the evaluation criteria to be used for each variable. More specifically, the goal is to identify all relevant stakeholders for the decision problem at hand, the different evaluation periods to be planned along the life history of the project and the evaluation variables to be considered to evaluate the performance for each evaluation period.

As presented in the previous sections, some performance variables cannot be directly measured and there exist hierarchical relations among different variables. Therefore, it is necessary to develop a breakdown analysis to identify hierarchical links between overall and elementary performance variables involved in a particular decision problem. The breakdown structure starts from the overall level of each performance dimension and ends with the elementary performance variables that can be directly qualitatively or quantitatively measured with the corresponding evaluation criteria. Business or industry knowledge as well as the project scope statement provide global guidelines to carry out this breakdown analysis. Methods and tools to identify the breakdown structure are necessary to perform the hierarchical decomposition. To simplify the breakdown process, a method is proposed to break down different performance dimensions on a common basis.

2.3.2.2 Quantification

Performance management should be developed based on the measurement of each elementary performance variable. Not all of the performance variables can be quantitatively expressed in numbers. It is however difficult to apply qualitative or linguistic expressions for performance management and decision support because they can be subjective and are not additive. So, the aim of the second phase is to develop quantitative expressions for measurement result of each evaluation criterion. Based on the selection of performance measurement criteria, elementary performance expressions are generated through performance evaluation methods and tools.

In this phase, different methods (for example, the numeric rating scale and the fuzzy logic values) are used in the methodology to transform the qualitative expressions into quantitative results. But in some particular situations where the number of evaluation criteria is limited or the situation cannot be assessed with numerical information, the performance of different alternatives can be directly compared with linguistic decision making systems (Merigó et al., 2016). In this case, the breakdown analysis and quantification operations are no longer necessary.

For intangible or fuzzy criteria that cannot be directly quantified (e.g. dirtiness of a part or beauty of an aesthetic car component), a numeric rating scale should be applied to translate qualitative linguistic descriptions into quantitative numbers (for instance, "1" for "very clean", "0.5" for "average" and "0.1" for "very dirty" for dirtiness). Compared to one single number, a fuzzy number is more accurate to express a linguistic expression regarding the uncertainty in project performance evaluation. For instance, the generalised triangular fuzzy numbers (Molinari, 2016) can be used to describe qualitative expressions.

2.3.2.3 Aggregation

Even when all performance criteria are quantitatively expressed, they are not necessarily appropriate for decision support or decision making, except if they can be integrated into a global quantitative expression. To this end, a phase of aggregation is necessary for almost all kinds of performance management and decision support problems.

This activity allows the calculation with all relative performance elements in order to obtain the overall performance evaluation of each assessment dimension. Through the selected aggregation operator, the normalised elementary performance expressions are transformed into global performance results for decision support.

The proposed process for this phase is made of two parts: normalisation and aggregation. The former is necessary because the units of measure vary from one criterion to another. They cannot be integrated into the same global expression without normalised results. Therefore, qualitative measures with different units should be transformed into formalised quantitative expressions, preferably between 0 and 1. The latter is the mathematical computation to obtain the final quantitative results for global expressions using usual information aggregation operators. Selecting the appropriate aggregation operators is very important and critical because they will have influence on the final result.

2.3.2.4 Decision support

Once the aggregation is finished for the several scenarios, the quantitative results of the overall performance for an industrial project or process (or system) can be evaluated. The objective of this phase is to present the overall performance in a visual way for the purpose of decision support.

In this context, a cost-value-risk (CVR) graphical representation is proposed to visually present the overall performance of each scenario to make easier decision making by comparing and ranking candidate solutions. To integrate the decision maker preference in this visual approach, different zones of aversion, acceptability and desirability should be determined for each dimension by the decision maker based on the particular decision context. This will make the comparison and ranking of different scenarios more effective. The following task consists in placing the aggregated results in a 3D space to facilitate the result interpretation and the decision making. In the case of monitoring an ongoing project, its overall performance at different evaluation periods can be presented in the same CVR space to obtain the trajectory that shows the evolution of the overall performance along a project life history.

Besides the graph with three axes, the decision maker can also decide to work with 2D graphs as well if s/he finds it more useful. For instance, he/she can use cost-value graphs or value-risk graphs or cost-risk graphs or the three altogether. This is a question of convenience and relevance in practice.

The overall description of the four-phase process for performance evaluation has been presented in this section. In the case of an industrial project, principles of the systems engineering (SE) framework are usually applied for user requirements specification and architecture design at the initial stage. While several elements of the proposed performance evaluation process have been borrowed from SE, we believe that the performance evaluation process can also be considered as a supplementary part of the verification and validation steps in the SE framework. This association is presented in the following section.

2.3.3 Relations with systems engineering approaches

Systems engineering (SE) approaches can be applied to explain and analyse complex situations or systems of the real world. Therefore, it is suggested to consider a large and complex industrial project as an abstract system to fully explore the problem and identify the necessary elements for performance measurement and management. Regarding the proposed BCVR performance evaluation method, some connections exist to link the methodology with systems engineering principles while monitoring the development of a project. We can mention:

- The operational environment of the system provides the context of the decision making problem (stakeholders, internal and external points of view…)
- The proposed methodology focuses on the "System of Interest" that is a deliverable (a product or a service) of an industrial project or process
- Cost, value and risk evaluations are developed based on different phases of the life cycle of the system during its life history
- A common basis for the breakdown structure development of each performance dimension is the expression of stakeholder objectives (requirements).

To develop an abstract system based on the real situation, various life cycle models (such as the waterfall, V and Agile Development models) are useful in defining the start, stop and process activities of different life cycle phases. Among them, the V model (Figure 2-18) is applied to visualise the systems engineering activities during the life cycle phases.

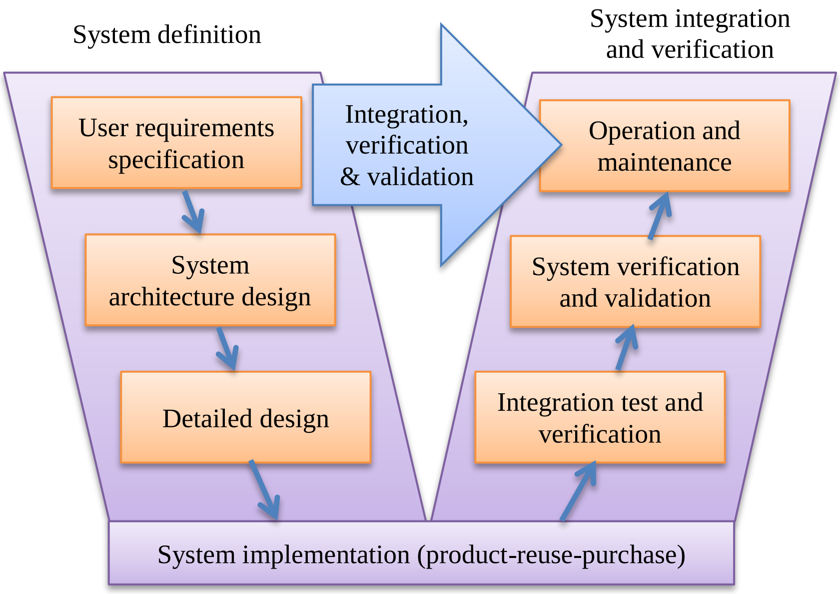


Figure 2-18. V model for systems engineering

In this model, time and system maturity proceed from left to right. It consists of three core parts: system definition, implementation and integration & verification processes. The system is developed from user requirements specification to architecture design and then detailed design in order to define the elements for the final system. With the time moving to the right, the entities are constructed to implement the system. Then, the right side of the model is executed to verify and integrate the system. Along a system life history, these processes iterate to ensure that a concept or design is feasible and that the stakeholder requirements remain satisfied and supportive to the evolved solution in each system life cycle phase.

The proposed BCVR performance evaluation method can be considered as a complementary methodology to guide the analysts or evaluators in the verification and validation step from the left to right side of the V model. This integration is illustrated in Figure 2-19.

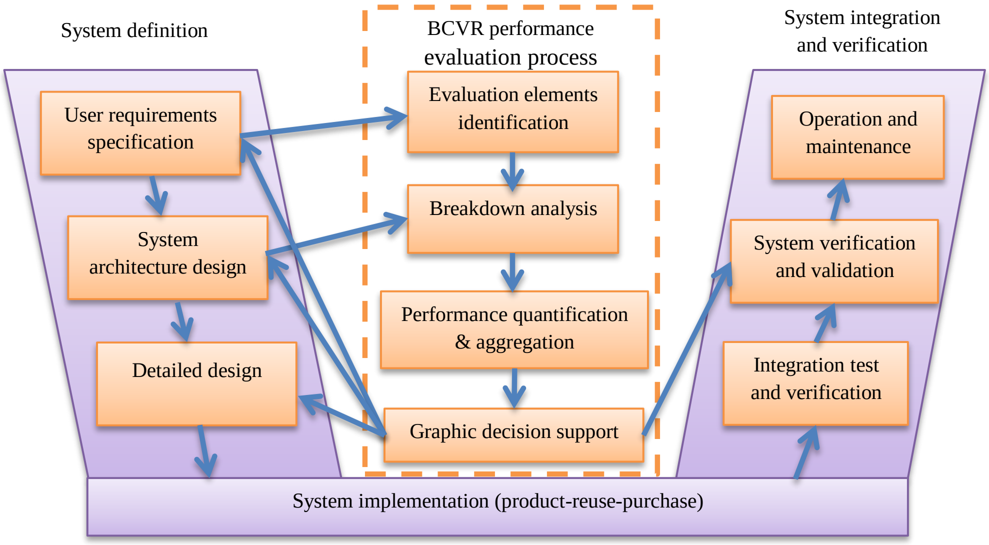


Figure 2-19. Integrated V-BCVR model

During the concept and development stages of a system, performance evaluation elements, such as stakeholder objectives or performance variables within each BCVR dimension, are identified based on the user requirements specification. Then, the system architecture design provides the necessary hierarchical relations among different components to ease the development of the breakdown analysis for cost, value and risk dimensions. The final outcome of the performance evaluation process will be applied to guide the evaluator to verify the in-process activities to ensure that the proposed baselines are acceptable in each stage of the system life cycle.

In this context, the systems engineering methods and tools, especially those for user requirements specification and system architecture design, can be applied to the proposed methodology in order to make easier relevant tasks. In the case of large and complex industrial projects, it allows the evaluator to develop the analysis in a systematic manner to ensure the accuracy of corresponding outcomes for operation in the following steps.

2.4 Conclusions

In this chapter, the analysis of the essential concepts, such as benefit, cost, value and risk, has been presented to define the basis for the proposed BCVR performance evaluation methodology. First, the necessary definitions for each performance dimension have been proposed and adapted to clarify the meanings of each dimension. Classifications of costs and risks have been proposed as reference lists or checklists for users of the methodology to make easier the identification of elementary costs and risks in the context of management of a specific project. Then, individual conceptual models have been developed as foundations based on essential concept analysis for the purpose of evaluation. These models have been aligned to build an integrated model linking the three quantitative dimensions (cost, value and risk) within a common logic to provide a global model. Finally, based on these relations, an analytical framework for performance expression has been proposed to comprehensively describe the overall performance of an industrial system or project in a flexible manner to meet the particular requirements of performance management and decision making contexts. Based on the principles of this framework, a global generic performance evaluation process based on the four evaluation dimensions (benefit, cost, value and risk) has been developed for opportunity evaluation of a new project, performance management or monitoring of ongoing projects.

The second part of the chapter focused on the global structure of the proposed methodology. First, some basic assumptions have been proposed to define the application context of the proposition. Then, the global structure of the methodology has been presented to describe the main functions of the four phases (identification, quantification, aggregation and decision support) of the proposed performance evaluation process and their relations. Finally, the link between the proposed methodology and systems engineering approaches, especially the system life cycle based on the V model, has been presented to show the possibility and advantage to integrate systems engineering methods and tools in terms of stakeholder objective specification and breakdown analysis in the BCVR performance evaluation process.

The aim of this chapter was to provide the basic concepts, global structure and theoretical principles of the proposed BCVR methodology for performance management and decision support. A simple example of performance analysis of a PhD doctoral project has been used to illustrate the relevant parts to facilitate the understanding of the theoretical proposals. This methodology is a set of tools and methods which provides guidelines to the analysts and decision makers in performance evaluation for the purpose of objective achievement. To generate the corresponding results, each phase contains different tools and methods that are selected according to the specific decision context and the evaluator preference. Detailed or specific methods and tools to be used in the BCVR methodology will be described in the following chapter to complete the methodological proposal.

CHAPTER III: BCVR PERFORMANCE EVALUATION: METHODOLOGY AND PROCESS

The analysis of the key concepts and the global structure presented in the previous chapter provides the theoretical principles at the upper levels for the development of the BCVR based performance evaluation methodology. Based on these elements, the detailed operations with a set of methods and tools of each phase (i.e. identification, quantification, aggregation and decision support) are developed to generate the corresponding deliverables at the lower levels for the implementation of the proposed methodology.

In this chapter, the research work and relevant results are presented in four sections, each one corresponding to one of the main phases of the proposed methodology. In addition, the example concerning the performance evaluation of a Ph.D. programme is used for each part to ease the understanding of the corresponding operations. The global structure of the chapter is shown in Figure 3-1.

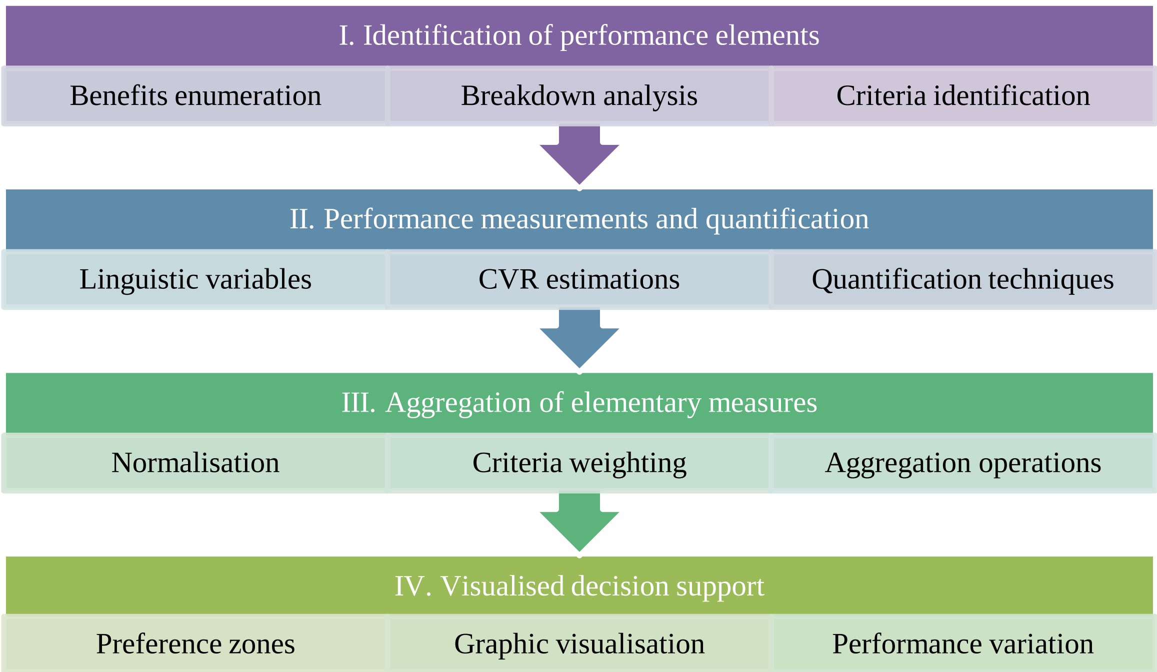


Figure 3-1. Structure of Chapter III

Each phase makes use of a set of methods and tools for the purpose of performance measurement and management. Some of them, such as cost-benefit analysis (CBA) (Mishan & Quah, 2007; Nas, 1996), Activity-Based Costing (ABC) (Cooper & Kaplan, 1988), balanced scorecard (BSC) (Kaplan & Norton, 1992), Failure Mode, Effects and Criticality Analysis (FMECA) (Tweeddale, 2003) and Analytic Hierarchy Process (AHP) (Saaty, 2012), are already widely applied to solve specific academic or industrial problems. They are therefore not discussed in detail in this document.

In addition, because the literature review for the current research has showed that none of the exiting PPM methods or tools can be used to comprehensively and concisely evaluate the overall performance to ensure the achievement of stakeholder objectives, some improvements can still be made based on the current development. The scientific contribution of the current research can be summarised in three points: (1) integration of different methods and tools to develop a methodology for efficient and effective performance evaluation, (2) proposition of a common basis to combine cost, value and risk estimation in the same framework and (3) development of a visualised tool to help decision makers in solving their decision making problems.

The proposed methodology can be considered as an association of a set of methods and tools which provide guidelines to decision makers in performance evaluation for the purpose of objective assessment. However, it should be noticed that there is no universal combination of methods and tools that can fit all kinds of decision problems. The selection of the specific methods and tools for each phase of the proposed methodology depends on both the evaluator preference and the availability of necessary resources for evaluation. The selected solutions should be adapted to the particular context of performance management and decision making.

3.1 Identification of performance elements

The purpose of this phase is to establish the necessary elements, such as stakeholder objectives, project life cycle phases, breakdown structures and evaluation criteria, for performance measurement and management for the subsequent phases of the methodology. The main deliverables of this phase can be summarised as:

- A list of potential advantages as project benefits (because if this dimension is considered, it will only be analysed in qualitative terms in the methodology as explained in Chapter II),
- Individual breakdown structures from the overall (or aggregate) level down to the elementary levels for the other three dimensions (cost, value and risk)
- A set of evaluation criteria for each evaluation variable used in the axes of cost, value and risk.

Therefore, this section is divided in three parts to present the selected methods and tools that are applied to generate the expected results.

3.1.1 Enumeration of project benefits

The main purpose of applying the BCVR based performance evaluation methodology is to increase the effectiveness and efficiency of human efforts in the decision making process. An organisation can benefit from using this methodology to guide the decision maker while evaluating the opportunity of a new project, managing performance or monitoring an ongoing project (respectively, a system). The same duality of the BCVR approach to project and system exists as it was done in Chapter II.

However, to simplify the text and do not bother the reader with a cumbersome style, the text of Chapter III only refers to project but can equally apply to any system.

Based on the specific application field and according to the adapted definitions presented in the previous chapter, benefit estimation includes both qualitative and quantitative analyses. If the concept of benefit can be defined in monetary terms in an economic context, the profit and loss account (PLA) analysis (Marginean et al., 2015) or the cost-benefit analysis (CBA) (Mishan & Quah, 2007) can be applied as the main evaluation methods and as the most basic assessment tools for studying the financial-economic performance of an industrial project.

Project benefits, either financial or non-financial, can be reflected by key performance indicators (KPI) (Kaplan & Norton, 1996). In addition, they may either be tangible or intangible (depending on whether they are material or measurable). For example, tangible project benefits can be time and cost savings and an intangible benefit may be the improvement of a stakeholder reputation or image of a company.

Due to the existence of intangible benefits, it is considered that in general the dimension of benefit has a qualitative nature and that, in most cases, it cannot be measured in practice. Instead, the list of potential advantages (or gains) is defined before or during the initial phase of a project. Good sources of information for establishing the enumeration of project benefits are the project scope definition (also called problem statement), the project charter (also called vision document) and relevant previous experiences of stakeholders in similar projects.

For example, the benefits of performing a doctoral project can be summarised as:

- Development of scientific research skills and other capacities
- Acquisition of potential opportunities for the future professional career
- Innovation and contribution to scientific results in a specific field

3.1.2 Breakdown analysis

Large projects are often characterised by multi-dimensional objectives as well as complex processes, leading to complex and interacting relations for performance measurement and management. In this context, the overall performance cannot be directly evaluated. A systemic breakdown analysis from the highest level to the lowest level is frequently carried out in order to obtain an operational solution to guide the analysis.

According to the analytical framework for performance expression presented in Chapter II, each performance dimension (i.e. benefit, cost, value and risk) includes a set of variables that are commonly used within an organisation to evaluate the overall performance of an industrial project. Except for simple cases, a given performance dimension does not contain only one variable. Therefore, performance variables should be identified in order to break down each dimension into various components that can be qualitatively or quantitatively measured (as described in Figure 2–10).

Except for benefit, the variables are directly enumerated at the initial stage of the analysis, each of the other three dimensions having particular characteristics. The dimension of cost is fully estimated by objective financial terms, while the dimensions of value and risk may contain quite a lot of subjective judgments. Cost variables are usually fully expressed by monetary terms. However, value and risk variable expressions contain numerous linguistic evaluations which should be quantified into numeric expressions for further analysis. In addition, the units of measure for value and risk variables are often not the same. It is necessary to normalise the different elementary measures before using aggregation operators to get the global value.

Therefore, the biggest challenge in this step is to develop a common basis to integrate the breakdown development of each performance dimension (cost, value and risk) into the same framework to make the analysis easy. As described in Chapter II, the concepts of objective or activity can be used as basic links to connect these three dimensions. So, it is proposed that, for most cases, the breakdown analysis can be developed either using strategic modelling or enterprise modelling methods.

This section will be divided into three parts to present the relevant methods and tools which are used in the proposed methodology. Firstly, the cost structure is presented for the identification of cost variables in most cases. Then, the strategic modelling techniques are described to show the basic links in terms of root cause and objective. Finally, enterprise modelling techniques, especially process modelling methods, are presented to indicate another way for developing the hierarchical breakdown analysis.

3.1.2.1 Cost structure

For most types of industrial projects, the structure and main components of the overall cost are usually well defined and are subject to less variation facing different decision contexts. It means that the cost analyses are often developed based on previous experiences on similar projects.

For instance, if the overall cost of a Ph.D. project is evaluated from the point of view of the Ph.D. candidate, the total cost is considered as the sum of the living expenses, transport costs, insurance costs and tuition fees during the whole project period. Similarly, for the university or laboratory, the overall cost of a Ph.D. project is the sum of the salary of the Ph.D. candidate and academic staff, the expenses of the material (office, energy and stationery), equipment, training, scientific communications and administration expenses. These cost structures are almost the same for any type of doctoral projects.

Therefore, it is considered that the breakdown structure for the dimension of cost can be directly identified for some well-known or recurrent situations or some typical classes of problems. If the cost components in one specific type of projects (for instance, IT development projects or building construction projects) are already well defined by the evaluators, that is, there already exits a standard cost structure for this kind of project (as shown in the example of the Ph.D. project), the cost breakdown structure can be simply developed with a copy-paste approach without the necessity to use strategic or enterprise modelling methods and tools.

However, in other cases, such as design of a product with brand new features for example, it is difficult to define the cost structure from previous experiences. Then, the breakdown analysis of cost can be developed using the common framework proposed in the following sections.

3.1.2.2 Objective modelling

The project scope definition or problem statement details the project deliverables and major objectives. For the purpose of objective achievement, it is necessary to develop a detailed objective expression at different levels to build a hierarchical structure for further breakdown analysis. For this purpose, two logics are applied to develop the top-down analysis of objectives. One way is the reverse thinking from the initial point using questions such as "*What are the elements that will cause the project failure?*" In this case, the root cause analysis is applied to develop the breakdown structure. Another way is the positive thinking with the initial question "*How can the best alternative be generated to ensure the project success?*" In this case, the method of value focused thinking (VFT) can be applied to generate the objective modelling structure.

3.1.2.2.1 Root cause analysis

To solve a problem, one must first recognise and understand what is causing the problem. A root cause is the most basic reason for an undesirable condition or problem (Wilson et al., 1993). Root cause analysis (RCA) is the process of identifying causal factors using a structured approach with techniques designed to a focus for identifying and resolving problems (Mahto & Kumar, 2008). It is a step by step method that leads to the discovery of faults or root causes. An RCA investigation traces the cause and effect trail from the end failure back to the root cause.

Doggett (2004) identified three RCA tools as generic standards for identifying root causes. They are the cause and effect diagram (CED), the interrelationship diagram (ID) and the current reality tree (CRT). He concluded that the CED and ID were perceived as better than the CRT at identifying cause categories, facilitating productive problem solving activity, being easier to use and more readable. Berrah and Foulloy (2013) mentioned that cause-effect tools, such as the dependencies graphs, the cognitive map and the value focus cycle time, are used for breakdown analysis of overall strategic in different methods, for example, quantitative model for performance measurement system (QMPMS) (Suwignjo et al., 2000), system measurement analysis and reporting technique (SMART) (Cross & Lynch, 1988) and integrated dynamic performance measurement system (IDPMS) (Ghalayini et al., 1997).

In the current research, the CED is considered as an effective tool for the handling of breakdown analysis. It helps to identify, sort and display causes of a specific problem by organising causes into major categories. In addition, it can graphically illustrate the relationships between a given outcome and all the contributing factors that influence the outcome. Figure 3-2 presents a cause and effect diagram for the doctoral project by using the Ishikawa (or fishbone) diagram (Ishikawa, 1989).

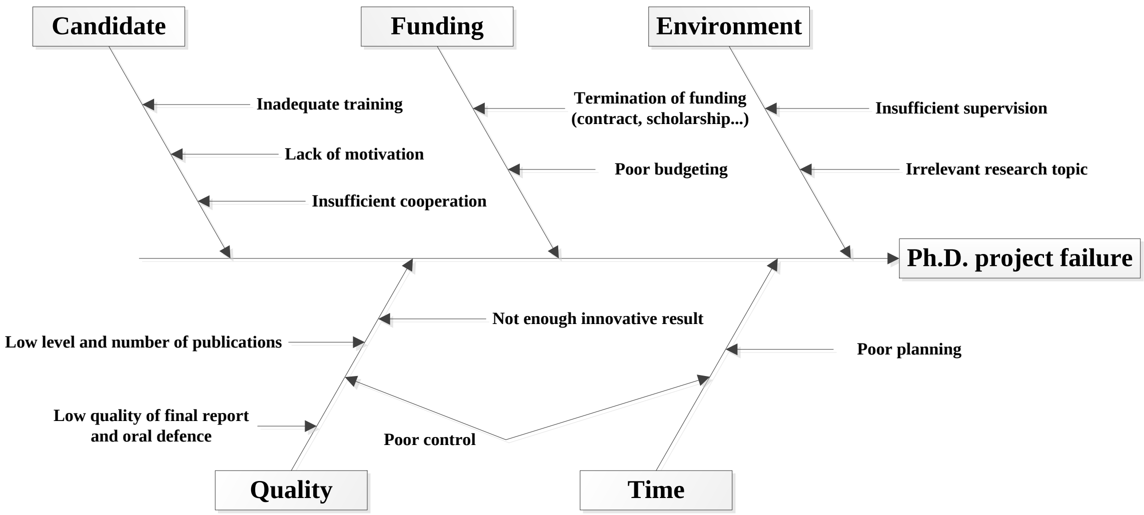


Figure 3-2. Cause and effect diagram for a doctoral project

Let us assume that the causes to the failure of a doctoral project can be grouped into five major groups: funding, time, quality, environment and candidate. The first group is related to financial resources of the project, the second category is about time management, the third group includes the causes on the quality of the scientific results, the fourth one takes into account the relevance of the topic and quality of the supervision and the last one is about the causes on the skill and motivation of the Ph.D. candidate.

Table 3-1. Combination of CED elements and performance variables

Dimensions	Variables	Basic elements in CED diagram											
		Insufficient supervision	Irrelevant research topic	Poor planning	Poor control	Termination of funding	Poor budgeting	Inadequate training	Lack of motivation	Insufficient cooperation	Low levels and number publications	Low quality of final report and defence	Not enough innovative result
Cost	Living expenses	√	√	√	√		√						
	International airfare						√						
	Material	√	√	√	√	√	√						
	Equipment		√	√		√	√						
	Training						√	√					
	Scientific communication										√		
	Administration						√					√	
	Additional cost	√	√	√	√		√	√		√		√	
Value	Duration			√	√	√	√		√	√			
	Quality 1				√			√	√	√	√	√	
	Innovation												√
	Publication										√		
Risk	Knowledge							√	√				
	Specification			√		√		√					
	Planning			√	√								
	Budget					√	√						
	Quality 2										√	√	√
	Resource									√			

It is assumed that elements in a CED can be directly associated to the performance variables of cost, value and risk which are identified based on the project scope statement or the KPI defined by the organisation. Therefore, it is proposed to use the CED as a common base to develop the breakdown analysis for each performance dimension. The combination between the elements in the CED diagram and the relevant performance variables (which have already been identified in the analytical framework for performance expression) concerning the example of the Ph.D. programme is shown in Table 3-1.

3.1.2.2.2 Value focused thinking

Value-Focused Thinking (VFT), developed by Keeney (1992), appears to be a good basis for the current research. Unlike other quantitative objectives modelling methodologies, the VFT method provides an explicit and articulated approach for objectives modelling and links it to the multi-attribute utility theory (MAUT). Keeney (1994) defines ten techniques to identify objectives by following a set of critical questions. These ten critical questions are listed in Table 3-2.

Table 3-2. Techniques for identifying objectives (Keeney, 1994)

Techniques	**Critical questions**
Develop a wish list	*What do you want? What do you value? What should you want?*
Identify alternatives	*What is a perfect alternative, a terrible alternative, a reasonable alternative? What is good or bad about each?*
Consider problems and shortcomings	*What is wrong or right with your organisation? What needs fixing?*
Predict consequences	*What has occurred that was good or bad? What might occur that you care about?*
Identify goals, constraints and guidelines	*What are your aspirations? What limitations are placed on you?*
Consider different perspectives	*What would your competitor or your constituency be concerned about? At some time in the future, what would concern you?*
Determine strategic objectives	*What are your ultimate objectives? What are your values that are absolutely fundamental?*
Determine generic objectives	*What objectives do you have for your customers, your employees, your shareholders, yourself? What environmental, social, economic or health and safety objectives are important?*
Structure objectives	*Follow means-ends relationships: why is that objective important? How can you achieve it? What do you mean by this objective?*
Quantify objectives	*How would you measure achievement of this objective? Why is objective A n times as important as objective B?*

In the VFT method, objectives are categorised into three types: *strategic*, *fundamental* and *means* objectives. The strategic objectives provide common guidance for all decisions in an organisation and form the basis for more detailed fundamental objectives appropriate for specific decisions. Fundamental objectives are about the ends that the decision maker desires in a particular decision context. Means objectives refers to methods to be used to achieve the ends.

To facilitate the identification of fundamental and means objectives, Keeney (1994) recommends to apply the "*Why is that important?*" test to distinguish them in a specific problem. If an objective is considered as one of the essential reasons for interest in the specific decision context, it is a fundamental objective. If the objective is thought to be important only because of its implications for some other objective, it is a means objective.

Concerning the execution phase of a Ph.D. project, Figure 3-3 presents an example of objective modelling with the VFT method.

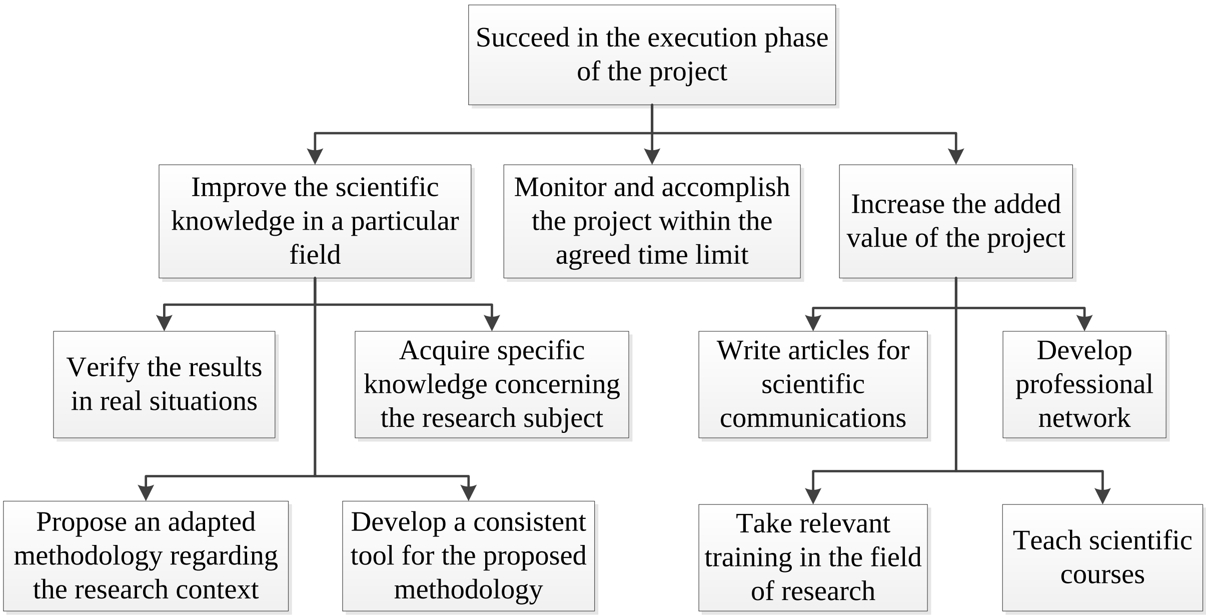


Figure 3-3. Objective modelling with the VFT method for the Ph.D. project

Similarly to the CED-based analysis, the following operation consists in identifying the links between the performance variables and the different means objectives in the objective modelling structure to develop the corresponding breakdown structure for the performance dimension of cost, value and risk. Table 3-3 presents the results regarding the example of the Ph.D. project.

Based on this combination, it is proposed to replace the means objectives in the modelling structure by the relevant performance variables to obtain the corresponding breakdown structure for cost, value and risk.

The main advantage of using the strategic modelling methods to develop the decomposition structure is that lacking of detailed information on the major activities in a project will not be a constraint for further performance measurement. It is adapted to the decision context in the opportunity evaluation for a new industrial project.

Table 3-3. Combination of means objectives and performance variables for the Ph.D. project

Dimensions	Variables	Means objectives in objective modelling structure								
		Verify in real situations	Acquire specific knowledge	Propose an adapted methodology	Develop a coherent tool	Accomplish within time limit	Prepare articles	Take relevant training	Develop professional network	Teach of scientific courses
Cost	Living expenses	√	√	√	√	√	√	√		
	International airfare									
	Material	√	√	√	√		√	√	√	√
	Equipment	√		√	√		√			√
	Training		√							
	Scientific communication							√		
	Administration									
	Additional cost									
Value	Duration	√		√	√	√		√		√
	Quality 1	√	√	√	√		√	√	√	√
	Innovation			√			√			
	Publication						√			
Risk	Knowledge		√	√	√					
	Specification	√	√	√	√			√		
	Planning	√		√	√	√		√		√
	Budget						√	√		
	Quality 2			√	√		√			√
	Resource	√				√			√	√

However, the analysis is more or less subjective because the result depends on the evaluator experience in relevant projects. In some cases, such as monitoring of an ongoing project, where the main processes or activities are already identified, enterprise modelling techniques and tools can be applied to support the development of the breakdown structure through the identification of the necessary activities for the realisation of the project or process at hand.

3.1.2.3 Enterprise modelling

Enterprise modelling techniques, based on functional decomposition, are suitable for breakdown analysis. The main techniques involved in the current research are IDEF0 and IDEF3 modelling languages (as described in Chapter I, Section 1.2.1) but BPMN or other similar techniques could have been used as well. An example concerning the execution phase of a Ph.D. project is shown in Figure 3-4.

It reads as follows: Once the literature review is done, an adapted methodology must be proposed and a decision support tool must be developed. Then, it is necessary to wait until both of the executed activities are completed to move on to the next phase of the project. Solid oriented arrows indicate the flow of control of the process while the dotted arrow indicates a communication from UOB 2 to OUB 3.

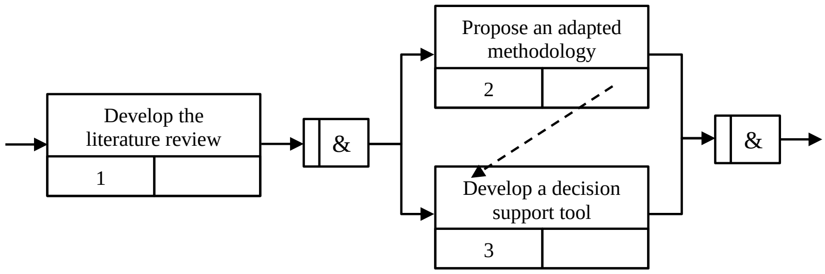


Figure 3-4. IDEF3 process modelling fragment of the execution phase of a doctoral project

The following operation consists in combining each UOB in the process model with the identified performance variables to develop the breakdown structure for each performance dimension. Table 3-4 presents the results regarding the example of the Ph.D. programme.

Table 3-4. Combination between UOB and performance variables for the Ph.D. project

Dimensions	Variables	UOBs in the process model		
		Develop the literature review	Propose an adapted methodology	Develop a decision support tool
Cost	Living expenses	√	√	√
	International airfare			
	Material	√	√	√
	Equipment	√	√	√
	Training	√		
	Scientific communication		√	√
	Administration			
	Additional cost			
Value	Duration	√	√	√
	Quality 1	√	√	√
	Innovation		√	√
	Publication		√	√
Risk	Knowledge	√		
	Specification		√	√
	Planning	√	√	√
	Budget			√
	Quality 2	√	√	√
	Resource	√	√	√

It is proposed to replace the UOBs in the process model with relevant performance variables to develop the corresponding breakdown structure for each performance dimension. Figure 3-5 presents an example of the breakdown structure of value for the execution phase of a doctoral project.

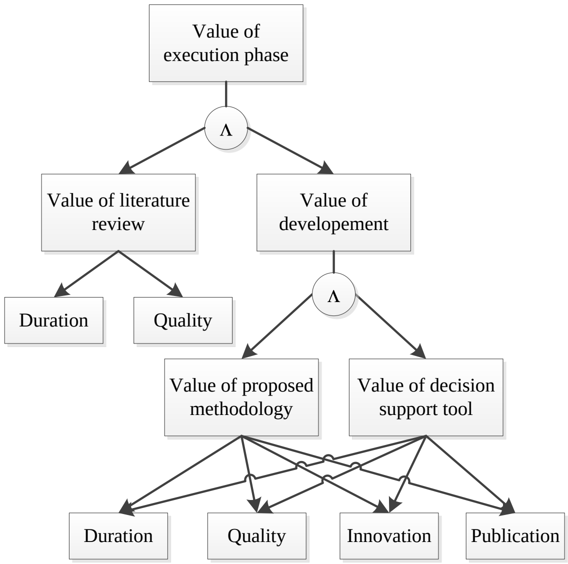


Figure 3-5. Value structure of the execution phase of a doctoral project

It should be noticed that the junction boxes in the IDEF3 model should be kept in the breakdown structures. Depending on the specific connectors (junction boxes) used in the process, the aggregation operations in the next methodological step should be adjusted. The detailed information will be presented in the corresponding section.

3.1.3 Performance criteria identification

Once the breakdown structures have been established, performance criteria should be identified in order to get elementary performance expressions (Taticchi, 2010). Each variable is then evaluated by one or several performance criteria, giving a set of qualitative and quantitative performance expressions for each performance dimension.

Besides the traditional criteria which are focused on financial performance, some new aspects are now considered by the evaluators. Berrah (2013) summarised some of them, such as supply chain management, integration of new technologies, sustainable development, relation with organisational structures and the extension of the concept "measurement" to "management", are involved in the expression of industrial performance.

To systematically describe a performance criterion (PC), the vision of "purpose, environment, organisation and behaviour" (Clivillé, 2004) is applied in the current research.

The purpose of a PC is to provide support for the selection, implementation or closure of a performance variable which is combined with a means objective.

The environment of a PC is a monitoring system and a test system. The monitoring system provides the following elements "objectives, performance variables, mechanisms for performance expressions" as the input of the PC. The test system provides the feedback from the real situation. The output of a PC is the elementary performance expression for further operations.

The organisation of a PC is presented under a system of performance criteria with interacted elements. The interactions are hierarchically based on the breakdown structure of each performance dimension. In addition, the interactions are reflected in the criteria weighting and selection of aggregation operators.

The behaviour of a PC is related to the corresponding performance variable. Over a specific evaluation period, the PC provides an elementary performance expression. In addition, the set of PCs are adjusted along the project life history based on the dynamic decision context.

In the current research, a performance criterion provides support for measurement of a specific performance variable based on the stakeholder objective and selected measurement method. Then, the performance criterion generates an elementary performance expression for the further operations in the proposed methodology.

3.2 Performance measurement and quantification

One deliverable of the identification phase is a list of performance criteria which are used to generate elementary performance expressions for the corresponding performance variables. These elementary expressions can be presented under qualitative (e.g. linguistic descriptions) or quantitative (i.e. mathematic descriptions) forms. However, only quantitative performance expressions are suitable for accurate performance evaluation. Therefore, it is necessary to present all elementary expressions under a quantitative form. The objective of this phase is to assess all identified performance criteria. Figure 3-6 shows a description of the main operation process in this step.

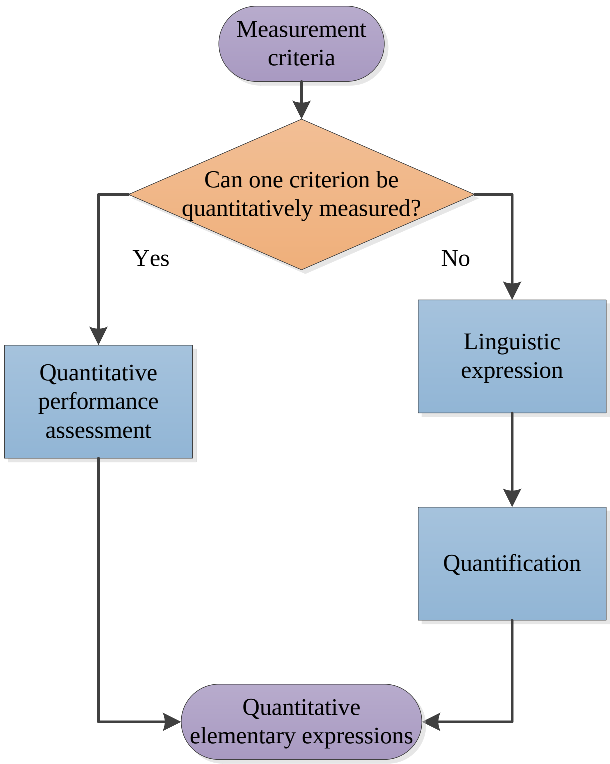


Figure 3-6. Main operation process in performance measurement and quantification

In this section, the methods and tools for performance measurement are described in the first part and the quantitative techniques are presented in the second part.

3.2.1 Linguistic variables

Most decisions are taken from an intuitive point of view or under the basis of only some very basic information elements (Merigó et al., 2016). In some situations, information items may be unquantifiable at first approximation due to their nature. So, it can be presented only in linguistic terms (for example, to evaluate the comfort of a car, terms such as "poor", "fair", "good" or "excellent" can be used). In other cases, the evaluation criteria cannot be assessed with usual exact numbers because either the available information for quantitative measurement is imprecise or the cost for its computation is too high (for example, when evaluating the speed of a car, linguistic terms such as "slow", "fast" and "very fast" can be applied instead of numeric values).

3.2.2 Performance measurement

As described in Chapter II, risk and uncertainty are the highest at the beginning stages of a project and the cost of making changes or correcting errors is extremely high at the end of the project. It should be noticed that the selection of evaluation methods for each performance dimension at the beginning stages impacts the final result of the project. Numerous methods and tools have been developed by researchers regarding benefit, cost, value and risk estimation. This section provides a non-exhaustive overview of these methods and tools. The objective is to find the proper references for the development of conceptual model for each dimension in the proposed methodology.

3.2.2.1 Methods and tools for cost estimation

Different methodologies have been developed for the purpose of cost estimation. Some researchers have classified the main cost estimation methods. Niazi et al. (2006) categorised different techniques into four groups: intuitive, analogical, parametric and analytical techniques for product cost estimation. Etienne (2007) proposed a non-exhaustive classification with three major groups based on parametric, analytical and analogical methods to classify cost estimation approaches commonly used in product design phase. Mauchand (2007) and Hassan (2010) added elements to complete the classification product cost estimation methods. These classifications are developed with the criteria such as available information and the phase in which the cost is estimated. Even if these classifications are developed for product cost estimation, it is considered that these techniques can also be applied in the context of project management. Figure 3-7 presents a comprehensive classification of cost estimation methods based on the works mentioned.

Analogical techniques use historical data of similar past cases to estimate the cost of the new project (or product). The identified similarities help to incorporate the past data into the new project so that the need to obtain the cost estimate from scratch is greatly reduced. Therefore, these approaches are helpful in making good estimates at the initialising phase, since the use of the past cost data to generate new estimates greatly minimises the estimation time. However, these techniques are applicable only when similar past expressions are available to incorporate the relevant cost data. In addition, they require a complete and content rich database to make easy the comparison analysis between the new alternative and past cases.

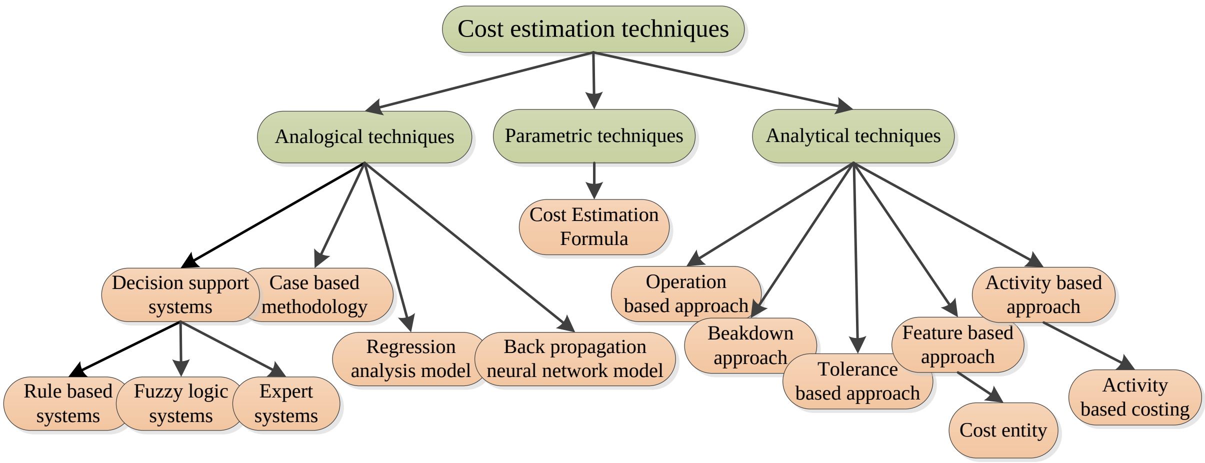


Figure 3-7. Classification of cost estimation methods

Parametric models are derived by applying the statistical methodologies and by expressing cost as a function of its constituent variables. These techniques could be effective in those situations where the parameters (for instance, cost drivers) could be easily identified. These techniques are generally used to quantify the unit cost of a given product.

Analytical techniques require decomposing a project into elementary units, operations and activities that represent different resources consumed along the project life history and expressing the total cost as the sum of different components. They can be further divided into different categories depending on the type of basic elements in the decomposition. Although these techniques need more time in estimation, they provide more accurate cost estimates and they are flexible to fit various evaluation contexts.

3.2.2.2 Methods and tools for value assessment

Some methods are used for value assessment, especially either to identify value and non-value creation activities or to ensure satisfaction of customer needs. In this section, three mains approaches, namely value engineering, value chain and value stream mapping, are presented to describe value assessment with respect to function analysis, activity analysis and lean management.

3.2.2.2.1 Value engineering

To evaluate the value of a product (as explained in Chapter II, Section 2.1.1.3), value engineering is applied by involving critical examination and analysis of the design of a component with reference to its functional value. It is a systematic and structured approach to accomplish the functions that the customer needs with the best functional balance among the quality, operational performance, manufacturing cost and product variations.

More specifically, if the customer need is a movement that the company pushes toward the product, the function will be the intermediary to dematerialise the product and express its role, its action, what it can do and how it behaves towards the need. In addition, the function is the first response to the need.

Value engineering is often executed by systematically following a multi-phase job plan. Depending on the application, the job plan may be varied to fit specific constraints. Chevallier (1989) proposed seven phases: defining the purpose of the study, information gathering, analysis of functions and costs, generation of alternative solutions, evaluation of solutions, recommendation and monitoring of execution. Similarly, Kiran (2017) proposed eight stages: general phase, information phase, functional phase, investigation phase, creative phase, evaluation phase, recommendation phase and follow-up phase.

For all situations, four basic phases in the job plan are: *information gathering* to determine important functions or performance characteristics for the product through the technique of function analysis; *alternative generation* to create various alternatives to perform the desired function; *alternative evaluation* to assess all the solutions in terms of meeting required functions and cost saving; *recommendation* to choose and present the best alternative to the customer for final decision.

During the value engineering programme, Function Analysis System Technique (FAST) is used as a graphical representation showing the logical relations between the identified functions of a product. It builds upon by linking the simply expressed, verb-noun (active verb and measurable noun) functions to describe complex systems in a logical sequence as shown in Figure 3-8. A FAST diagram is generated based on three key questions: "*How* to achieve the function?", "*Why* apply the function?" and "*When* use the function?)".

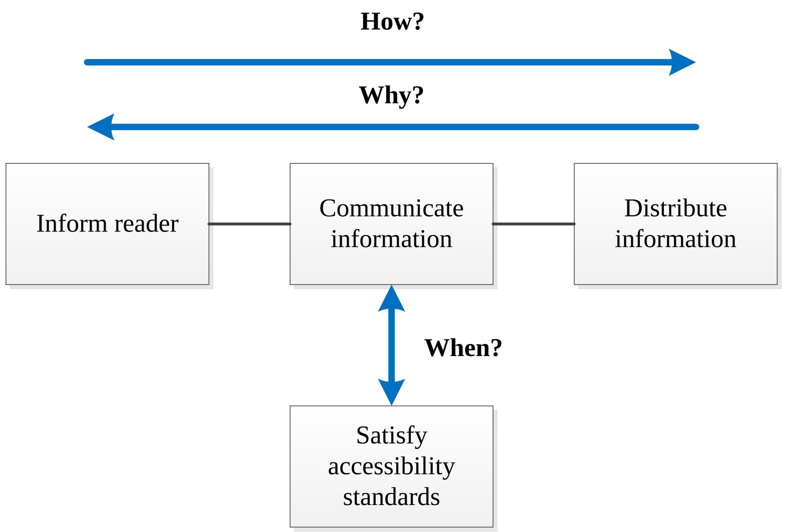


Figure 3-8. Example of a FAST diagram for an information system

3.2.2.2.2 Value chains

A value chain, as originally proposed by Michael Porter in 1985 but revised later (Porter, 1998), is a set of activities in a specific company performed to deliver a valuable product or service for customers, i.e. to create value. Value chain analysis is supported by a graphical notation used to describe how activities of a manufacturing or service company affect competitive advantage through their impact on the value chain.

Porter's generic value chain distinguishes primary activities (inbound logistics, operations, outbound logistics, marketing & sales and service) from support activities (infrastructure, human resource management, technological development and procurement), as shown in Figure 3-9. It is considered that products or services pass through this chain of activities to gain some value at each step. In the end, the goal is that the chain of activities gives the product or the service more added value than the sum of elementary values of all activities.

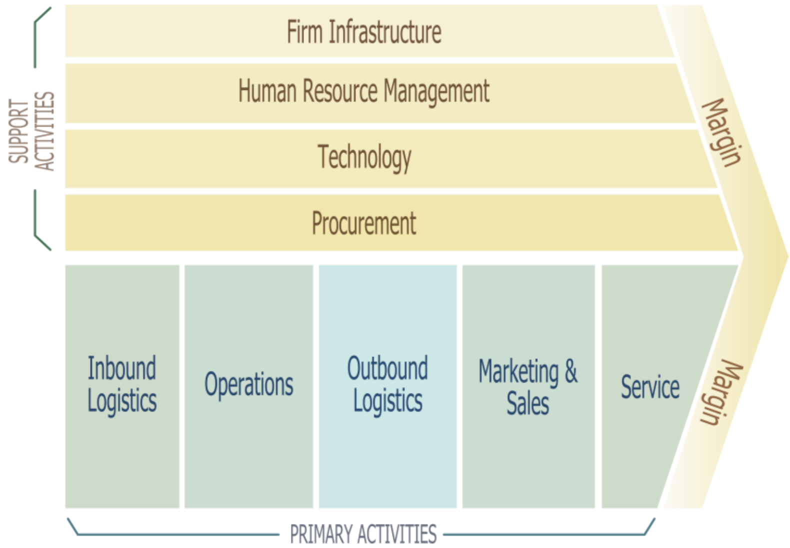


Figure 3-9. The generic value chain (Porter, 1998)

Thanks to value chain analysis, a company can efficiently assess value generated through its business activities and elaborate its strategic plan. By analysing the upstream and downstream information along the value chain, the company can introduce new business models to make improvement in value creation. Value added activities and non-value added activities can easily be analysed. The approach can also offer a meaningful alternative to evaluate a company while lacking of data from direct competition for comparison (benchmarking). Once the contributing parts of the company have been identified, other approaches, such as SWOT (Strengths-Weaknesses-Opportunities-Threats) analysis, can be used in conjunction with the value chain to assess how these parts can be improved.

3.2.2.2.3 Value stream mapping

Value Stream Mapping (VSM) is a Lean Management method for analysing the current state and designing a future state of manufacturing systems to depict and improve the flows of inventory and information from the beginning of a complete value creation process through to the customer (Rother & Shook, 2003). The method can be considered as a special type of flow chart that usually employs standard symbols (known as "the language of Lean") to represent items (materials, designs or customer needs) and process.

The objective of VSM is to provide optimum value to the customer with minimum wastes, inefficiencies, non-valued added steps (Tyagi et al., 2015). Although VSM is often associated with manufacturing, it can also be applied to other disciplines such as supply chain, product development, software development and administrative process.

Based on Lean thinking principles, Mascitelli (2007) classified tasks associated with VSM into three categories: value added (tasks that really create values), non-value added but necessary (tasks that may not create values but are necessary under current circumstances) and waste (tasks that have no value for customers). It is important to increase the ratio of value added time while reducing the ratio of non-value added but necessary and the waste.

Figure 3-10 shows the high level phases in implementation of VSM. The aim of the initial analysis is to identify the main "pain points (real or perceived problems)" and the potential processes to be improved based on the total time in the system and total cost of resulting component. Then, the current state is mapped with the prospect of reaching to the future state. The objective is to create an action plan to reach the future state by eliminating wastes. Finally, some experiments using the Deming cycle (Plan-Do-Check-Act) are performed to gain better results in reaching the future state.

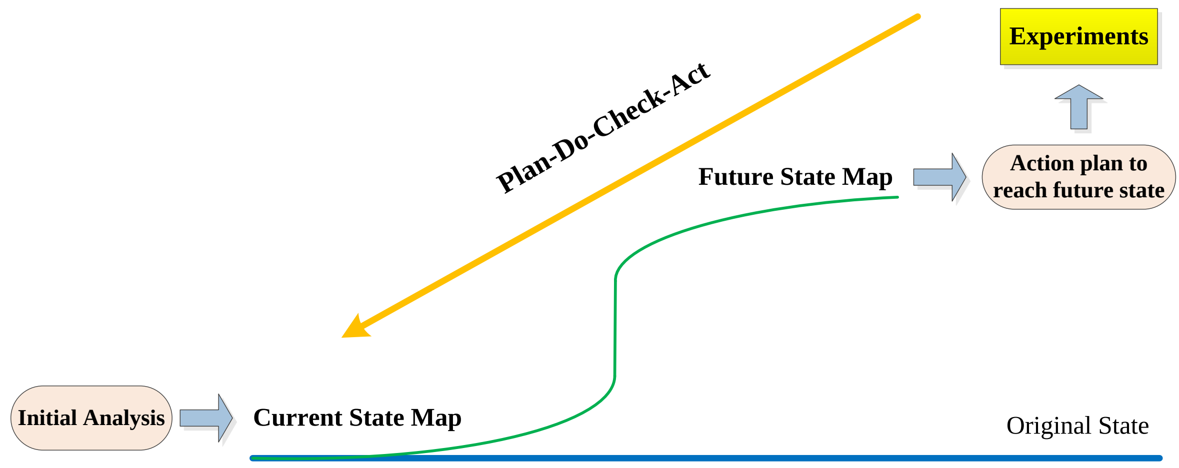


Figure 3-10. VSM implementation phases

To conclude this section, it can be said that these three methods are commonly applied to identify value creation locus and to assess value, which is defined as a ratio between customer satisfaction and total cost. The aim of value engineering is to increase customer satisfaction through critical analysis of functional value while designing a product. The value chain framework offers the management a powerful analysis tool for strategic planning. VSM is used to reduce lead time and eliminate waste while improving or at least maintaining the level of performance and quality.

In the context of this Ph.D. thesis, these methods can be useful to identify and analyse value creation activities. They can be used as preliminary analysis to identify where value is created. However, based on the definition of value proposed in the thesis, it is necessary to identify value components for value assessment in relation to some objective satisfaction. Unfortunately, these methods provide little help for this second task.

To do so, qualitative or subjective approaches (such as individual surveys, group brainstorming or activity characterisation) and qualitative approaches are the main tools to generate the components of value assessment expressions with respect to customer or stakeholder satisfaction.

In addition, it is important to note that value assessment should be adapted in terms of specific analysis for each case. Obviously, there is a lack of common methodology to determine the components of value expression in a systematic way in the general case. Each case becomes a specific problem.

3.2.2.3 Methods and tools for risk analysis

3.2.2.3.1 Risk management process

Risk management is a process combining several assessment and decision phases which precede and accompany the execution of an activity to consolidate the achievement of its objectives (Desroches et al., 2009). According to the standard ISO 31000 (2009), this process should be an integral part of management, embedded in the culture and practice of managers and tailored to the business processes of the organisation. It belongs to the following activities as shown in Figure 3-11.

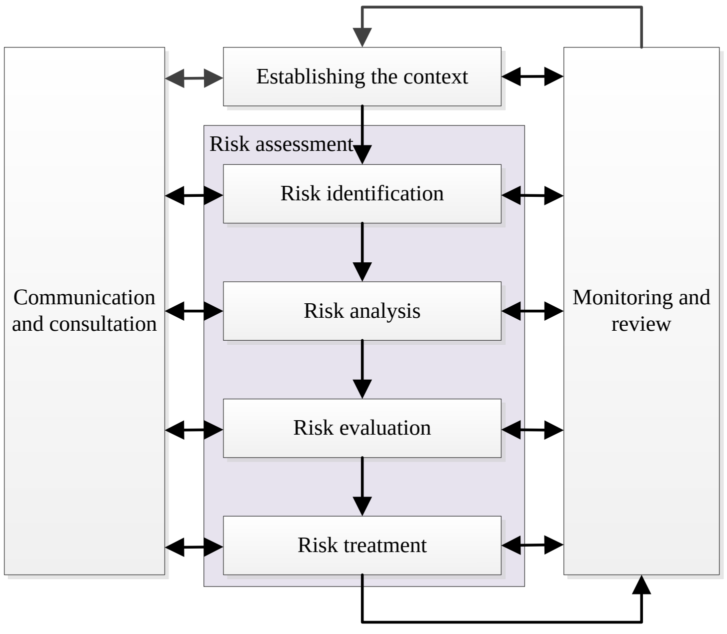


Figure 3-11. Risk management process (ISO 31000, 2009)

Effective external and internal communication and consultation with relevant stakeholders should be developed at an early stage regarding the risk itself, the causes, the consequences and the measures being taken to mitigate it. With integration of the various perceptions of risk from several stakeholders, communication and consultation should take place during all stages of the risk management process to ensure that stakeholders understand the reasons why particular actions are required.

By establishing the context, the decision maker clarifies the objectives, defines the external and internal parameters to take into account while managing risk and setting the risk criteria for the remaining process. Risk criteria, being consistent with the predefined risk management policy, should be defined at the beginning of the risk management process and be continually reviewed.

During risk identification, the sources of risk, areas and gravity of impacts, causes and potential consequences of events are comprehensively identified in order to generate a nearly exhaustive list of risks based on these events that might influence the achievement of the objectives. They are considered as basic components while evaluating the overall risk of an industrial system.

It should be noticed that if an essential risk (for example, the environmental impact of an industrial project) is missed in this step, it will be difficult to include it in further analyses (for instance, breakdown analysis, qualitative or quantitative measurement) which are developed based on the deliverables of risk identification. Therefore, all relevant risks, even if their source or cause may not be obvious, should be included in this step. Therefore, the list of elementary risks should be regularly verified at the beginning of each performance evaluation.

Risk analysis involves developing an understanding of the risk factors in terms of their causes and sources, consequences and their likelihood and other attributes of the risk. It provides an input to risk evaluation in terms of whether a risk needs to be mitigated and what are the most appropriate treatment methods. The degree of risk analysis depends on the type of risk, the purpose of the analysis, available information, data and resources. Depending on the particular decision context, the analysis can be qualitative, quantitative or a combination of both.

Based on the outcomes of risk analysis, risk evaluation assists the evaluator to determine which risks need to be mitigated and the priority for mitigation implementation. It can lead to a decision to either undertake further analysis or maintain existing controls.

Risk treatment involves selecting one or more options for modifying risks and implementing these options. According to the standard ISO 31000 (2009), the most appropriate risk treatment options involve comprehensive considerations on costs and efforts of implementation against the benefits derived, with regard to legal, regulatory, social responsibility and the protection of the natural environment.

Monitoring and review, involving regular checking and surveillance, should be clearly defined and encompass all aspects of risk management process. They can ensure effective and efficient controls in operations and be used to detect emerging changes in the external and internal contexts. The results of risk monitoring and review can be used as inputs to review the risk management process.

In most risk analysis problems, the potential causes and consequences are priority elements that are often considered by the evaluator at the initialisation phase with the considerations of the functional, material, informational and operational processes. Therefore, process hazard analysis (PHA), being developed with the functional or operational architecture of a system, is usually applied to assess the potential hazards associated to an industrial process. According to Desroches et al., (2009), the PHA is developed through two steps: PHA system and PHA scenario.

PHA system is about identifying the hazardous situations that are caused by system exposure under structural and conjectural hazards during the life history of the system. PHA scenario aims to analyse the hazardous situations, evaluate the initial risks, define the operations and manage the residual risk.

3.2.2.3.2 Tools and techniques for risk analysis

Risk assessment, especially the risk analysis, provides a guide for the evaluators in the performance measurement step. Based on how the techniques apply risk analysis, the international standard IEC/FDIS 31010 (2009) classified the techniques into four groups: (1) consequence analysis; (2) qualitative, semi-qualitative or quantitative probability estimation; (3) assessing the effectiveness of any existing controls and (4) estimation the level of risk. Based on this classification, different tools and techniques can be used and their applicability is evaluated as shown in Table 3-5.

Table 3-5. Tools and techniques for risk analysis (adapted from (ISO 31000, 2009))

Tools and techniques	Consequence analysis	Probability estimation	Level of risk estimation
Hazard and operability studies (HAZOP)	Strongly applicable	Applicable	Applicable
Hazard analysis and critical control points (HACCP)	Strongly applicable	Not applicable	Not applicable
Environmental risk assessment	Strongly applicable	Strongly applicable	Strongly applicable
Structure “What if?” (SWIFT)	Strongly applicable	Strongly applicable	Strongly applicable
Scenario analysis	Strongly applicable	Applicable	Applicable
Business impact analysis	Strongly applicable	Applicable	Applicable
Root cause analysis	Strongly applicable	Strongly applicable	Strongly applicable
Failure mode and effect analysis (FEMA)	Strongly applicable	Strongly applicable	Strongly applicable
Fault tree analysis	Not applicable	Strongly applicable	Applicable
Event tress analysis	Strongly applicable	Applicable	Applicable
Cause and consequence analysis	Strongly applicable	Strongly applicable	Applicable
Cause and effect analysis	Strongly applicable	Not applicable	Not applicable
Layer protection analysis (LOPA)	Strongly applicable	Applicable	Applicable
Decision tree	Strongly applicable	Strongly applicable	Applicable
Human reliability analysis	Strong applicable	Strongly applicable	Strongly applicable
Bow tie analysis	Applicable	Strongly applicable	Strongly applicable
Reliability centred maintenance	Strongly applicable	Strongly applicable	Strongly applicable
Markov analysis	Strongly applicable	Not applicable	Not applicable
Bayesian statistics and Bayes nets	Strongly applicable	Not applicable	Not applicable
FN curves	Strongly applicable	Strongly applicable	Applicable
Risk indices	Strongly applicable	Strongly applicable	Applicable
Consequence/probability matrix	Strongly applicable	Strongly applicable	Strongly applicable
Cost/benefit analysis	Strongly applicable	Applicable	Applicable
Multi-criteria decision analysis (MCDA)	Strongly applicable	Applicable	Strongly applicable

In the current research, the elementary risk is expressed through the estimation of either one of the three aspects (the consequence, probability and the level of risk) or on a combination of more than one aspect.

If the analysis is focused on one aspect, the evaluator chooses the corresponding tools and techniques according to the particular decision context. The analysis results can be identified with the previous data in similar projects or through subjective judgement (for example, individual survey or brainstorming) from a group of experts.

In other cases, the evaluator may prefer to integrate different aspects of risk in the analysis. For example, during the design, manufacture or operation of a physical system, methods such as failure mode and effect analysis (FEMA) and failure modes and effects and criticality analysis (FMECA) (Stamatis, 2003) express a risk in terms of a mode criticality index or a risk priority number (RPN).

The mode criticality index (MCI) is a measure based on the probability of mode failure for the system. It is obtained by multiplying three elements as shown in Equation 3-1.

$$\mathrm{MCI} = P \times R \times T \tag{3-1}$$

Where, P is the failure effect probability, R is the mode failure rate and T is the operation time of the system.

The RPN is a semi-quantitative measure of criticality obtained by multiplying numbers from rating scales (usually between 1 and 10) as shown in Equation 3-2.

$$\mathrm{RPN} = C \times L \times A \tag{3-2}$$

Where, C is the consequence of failure, L is the likelihood of failure and A is the ability to detect the problem.

The mode criticality index is preferred when each of the involved terms can be quantitatively defined and all considered failure modes have the same consequences. Otherwise, one can apply the RPN for risk analysis.

The selection of a tool and technique to be applied for risk analysis depends on a number of factors, such as: the complexity of the process, the length of time a process has been in operation and if the process is unique or industrially common.

3.2.3 Quantification techniques

Resulting from different methods and tools for performance measurement, the performance expressions involved in a specific performance management process for a given problem are heterogeneous. Some of them are quantitative (expressions with numeric numbers) and others are qualitative (linguistic expressions). In addition, some measures are objective (the measures are not influenced by the evaluator preference) while others are generated from subjective judgments (the measures vary with different evaluator perceptions). For the purpose of decision support, various performance expressions with different attributes should be unified into the same structure. Therefore, it is necessary to convert these elementary performance measurements into a quantifiable way to ease decision making. This transformation gives basic measurements which can be aggregated into an overall performance expression for each dimension of cost, value and risk.

Because qualitative performance expressions cannot be directly applied to performance evaluation (they can be subjective and are not additive), they must be transformed into quantitative expressions. It should however be noticed that in some particular situations where the number of evaluation criteria is limited or the situation cannot be assessed with numerical information, the performance of different alternatives can be directly compared with linguistic decision making systems (Merigó et al., 2016). In these cases, the breakdown analysis and quantification operations are no longer necessary.

3.2.3.1 Numeric rating scale

For intangible criteria that cannot be directly quantified (e.g. dirtiness of a part), a numeric rating scale should be applied to translate qualitative linguistic descriptions into quantitative numbers (for instance "1" for "totally clean", "0.8" for "very clean", "0.5" for "average" and "0.1" for "very dirty"). This approach has been widely used in practice to generate quantitative evaluation results for the performance criteria that cannot be directly assessed by mathematical measurement.

Likert scaling, originally introduced by Rensis Likert (1932), is considered as the most widely used rating scale to indicate levels of agreement with a declarative statement (Li, 2013). A Likert scale is the sum of responses on several Likert items, which are statements associated with quantitative expressions on subjective or objective evaluation dimensions (the most commonly used dimension is level of agreement or disagreement). For example, a typical five-level Likert item is: 1 for "strongly disagree", 2 for "disagree", 3 for "neither agree nor disagree", 4 for "agree" and 5 for "strongly agree". A well designed Likert scale should state the opinion, attitude or belief being measured in clear terms and use appropriate expressions.

For example, for the evaluation of the publication variable of a Ph.D. project, the selected criteria could be: (1) number of publications, (2) type of publications and (3) scientific level of publications. Then, the quantification method could be a numeric scale defined by experts based on previous experience. An illustration is shown in Table 3-6.

For example, a doctoral candidate has made 3 publications: 1 in an international journal, 1 in an international conference and 1 in a national workshop. According to the numeric scale in Table 3-6, the quantitative results of each criterion are: (1) 5 for "Number of publications", (2) 5.67 for "Type of publications" and (3) 6.67 for "Scientific level of publications". Because there are three elementary expressions for the "publication" variable, the results for all criteria should be aggregated into one global expression. Then, the evaluation process goes to the next step: aggregation.

Table 3-6. Illustration of numeric scale for publication evaluation of Ph.D. project

Number of publications	Numeric scale (from 0 to 10)
6 or above	9
4-6	7
1-3	5
0	0
Type of publications	Numeric scale (from 0 to 10)
Workshop or conference	5
Journal	7
Scientific level of publications	Numeric scale (from 0 to 10)
National	4
International	8

The advantage of this approach is that it is easy to apply without requirements on detailed data for mathematical computations. However, the results presented by one single number are largely influenced by the evaluator preference and his/her subjective judgement.

To decrease the subjectivity of the evaluation results for decision making, the evaluation results from a group of evaluators (for instance, expert team or customer survey) are taken into consideration instead of that from only one or several evaluators.

3.2.3.2 Fuzzy sets and fuzzy numbers

There is another way to increase the accuracy of the evaluation results. Compared to one single number, a fuzzy number is considered to be more accurate to express a linguistic expression regarding the uncertainty in project performance evaluation.

3.2.3.2.1 Fuzzy sets

Zadeh (1965) introduced the fuzzy sets theory (FST) to deal with the uncertainty and vagueness. A major contribution of FST is its capability of representing uncertain data (for instance, linguistic expressions). A fuzzy set is defined as "*a class of objects with a continuum of grades of membership. Such a set is characterized by a membership function, which assigns to each object a grade of membership ranging between zero and one*" (Zadeh, 1965). Based on this definition, Hanss (2005) described a classical set as "*a collection of objects or elements out of some universal set which are characterized by some well-defined common property*".

A classical set can be described in different ways. The first way is to list all elements that belong to a set with a finite, countable number of elements. For example, the fuzzy set, which is used to describe a project implied risk, can be defined as:

A = {extremely intolerable, very intolerable, intolerable, acceptable, desirable}

The second way is to define the set by giving the common property that it is possible to rank these elements to be included in the set. Hence, a statement is defined to express the condition for membership. For example, the fuzzy set, which is used to describe the alternatives with acceptable value, can be described as:

A= {x|A(x)}

with A(x) = "x is the alternative with an quantitative overall value between A and B "

The third way to define the set is to define the member elements by using a characteristic function, which can be expressed as:

$$\mu_A : X \rightarrow \{0, 1\}$$

If $\mu_A\ (x) = 1, x \in X\ and\ if\ \mu_A\ (x) = 0$, x is not included in the set X.

In the current work, the elementary performance measurements for qualitative criteria are expressed by a set with countable number of linguistic expressions by following the first way. To integrate these qualitative expressions with other quantitative measurements in further operations of the proposed methodology, the linguistic elements should be replaced by quantitative numbers.

3.2.3.2.2 Fuzzy numbers

The fuzzy sets which are defined on the universal set of real numbers are of particular importance. Under certain conditions, they may be viewed as fuzzy numbers. There exist different types of fuzzy numbers according to the types of membership functions. Some of them are of particular importance, hence it is proposed to apply the triangular fuzzy number method (Molinari, 2016) to describe linguistic expressions in the current research.

The triangular fuzzy number (TFN) (or linear fuzzy number) method is one of the most frequently used methods in practice for fuzzy numbers, because of its rather simple membership function with the linear type. A TFN is denoted simply as (a, b, c), as shown in Figure 3-12.

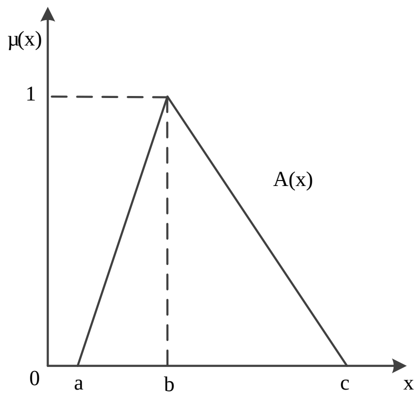


Figure 3-12. Triangle fuzzy number

The parameters a, b and c (a ≤ b ≤ c), respectively, denote the smallest possible value, the most promising value, and the largest possible value that describe a fuzzy event. The membership function of TFN is shown in Equation 3-3.

$$\mu_A(x) = \begin{cases} 0, & if\ x \le a \\ \frac{x-a}{b-a}, & if\ a < x < b \\ 1, & if\ \ x = b \\ \frac{c-x}{c-b}, & if\ b < x < c \\ 0, & if\ x \ge c \end{cases} \tag{3-3}$$

Regarding the set of linguistic expressions for a certain performance criterion, each description is considered to be one TFN to transform the subjective qualitative expressions into quantitative measurements. Table 3-7 presents an example of fuzzy based quantitative expression of project implied risk elements.

Table 3-7. Fuzzy based expression of project implied risk elements

Risk descriptions	Triangular fuzzy numbers
Extremely intolerable	(.7, .9, 1)
Very intolerable	(.5, .7, .9)
Intolerable	(.3, .5, .7)
Tolerable	(.1, .3, .5)
Acceptable	(0, .1, .3)
Desired	(0, 0, .1)

The decision makers will define one TFN for each criterion according to their preferences and the particular decision context. All performance criteria are transformed into quantitative expressions at the end of this step.

3.3 Aggregation of elementary measures

According to decision maker preferences in a particular decision context, measurement criteria are selected for each CVR dimension and a multi-criteria analysis is proposed to get a precise result for performance evaluation of each alternative in order to compare different solutions.

In today's fast changing and more complex environments, companies are taking more and more performance evaluation criteria into account to comprehensively evaluate the performance of their different projects or processes. Therefore, one of the biggest challenges while measuring performance is the increase in the proliferation of various types of performance indicators in the context of multiple decision making criteria. Form the point of view of the evaluators, this raises the need to have aggregated performance measurement to help the decision makers to evaluate the overall performance.

The objective of aggregation is to combine the information contained in different elements (an n-tuple of input values) by means of a single representative value. Different aggregation methods are applied in numerous applications in various areas. For decision making problems, this operation provides the evaluator with a scientific basis for project alternative comparison because only performance expressions at overall levels can be directly used for decision support.

In the literature, there is a wide range of information aggregation operators (Grabisch et al., 2011). Some very well-known ones are the weighted average, the probabilistic aggregation and the ordered weighted average (Yager & Kacprzyk, 1997). These operators have also been studied for linguistic information resulting in the linguistic weighted average, the linguistic probabilistic aggregation and the linguistic ordered weighted average (LOWA) operator (Herrera & Herrera-Viedma, 2000).

Based on these aggregation operators, a generic expression of aggregation computation is shown in Equation 3-4.

$$\mathrm{Ag}(V_k) = \mathrm{ag}\big((w_{k1}, V_{k1}), (w_{k2}, V_{k2}), \cdots, (w_{ki}, V_{ki}), \cdots (w_{kn}, V_{kn})\big) \tag{3-4}$$

Where, $\mathrm{Ag}(V_k)$ is the aggregate result of performance dimension k (cost, value or risk); V_{ki} is the elementary expression of criterion i of the variable ki; w_{ki} is the weight of criterion i of the variable ki according to the preference of a decision maker, in most cases, $\sum_{i=1}^{n} w_{ki} = 1$; ag is the aggregation operator. Figure 3-13 presents the main operation process of this phase.

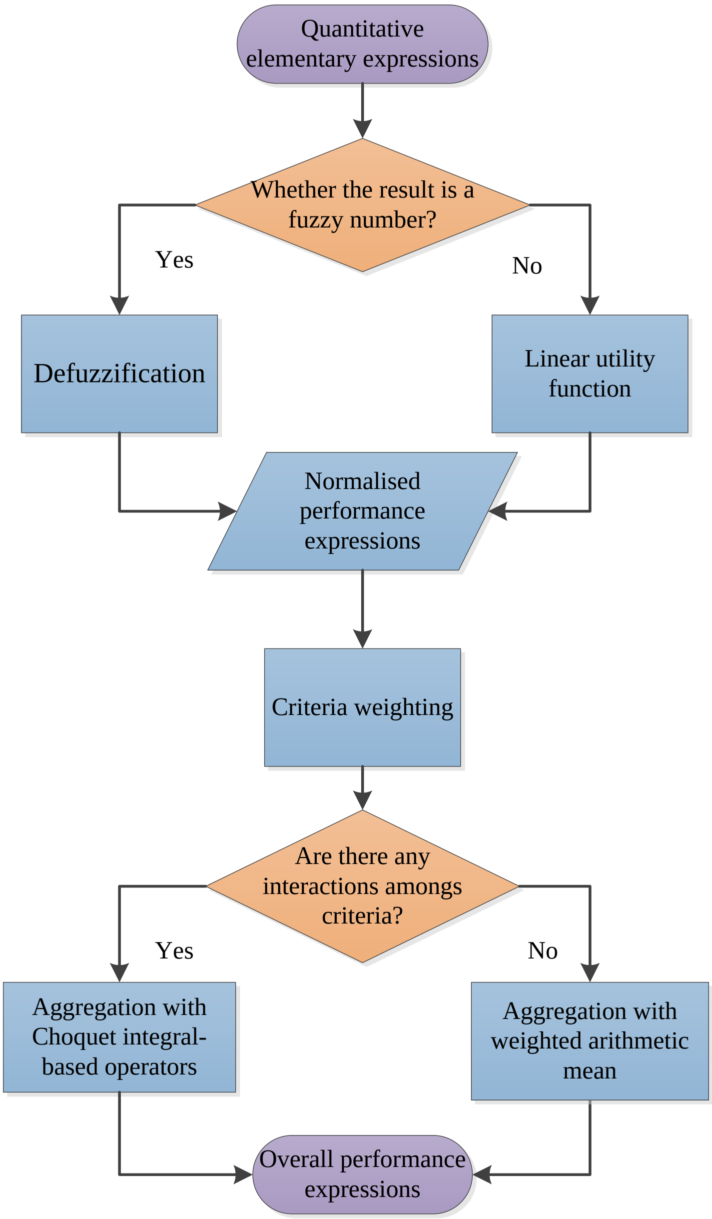


Figure 3-13. Main operation process of the aggregation phase

However, for the dimension of cost, if all elementary expressions are described by monetary terms, the overall cost is specifically computed as the cumulative sum of all elementary expressions and the overall cost expression is normalised for consistent performance expression with value and risk.

For the other cases, the aggregation phase contains three main tasks: (1) normalisation of elementary performance expressions, (2) criteria weighting based on the decision maker preferences and (3) aggregation mechanism based on the results of the previous steps. The detailed operations of each step will be presented in this section.

3.3.1 Normalisation

Each performance criterion is either qualitatively or quantitatively expressed by means of the selected performance measurement method. However, different elementary measures often have different units. It is difficult to directly aggregate them into one overall quantitative expression. So, the first step is to transform these acquired measures into the same unit. This is called commensurability.

Berrah and Clivillé (2007) proposed one way to simplify this problem by translating the elementary measures into satisfaction degrees, which are called elementary performance expressions. This kind of performance expression is a comparison of the acquired measures with an objective defined according to the control strategy considered. The performance expression can be formalised by the expression shown in Equation 3-5 (Berrah et al., 2000) .

$$\mathrm{P}: \mathrm{O} \times \mathrm{M} \rightarrow \mathrm{E} \tag{3-5}$$

$$(\mathrm{o}, \mathrm{m}) \rightarrow \mathrm{P}\ (\mathrm{o}, \mathrm{m})$$

Where, O, M and E are the universes of discourse of the objectives, of the measures and of the performance expression. The mapping P denotes a comparison operator such as a distance operator or a similarity operator. If the satisfaction of the objective is flexible, P is known when the objective is declared; if the expression of the objective is uncertain, P must be defined separately.

In the proposed framework, it is proposed that the performance criteria can be divided into two categories: quantitative and qualitative criteria. The classification is based on whether one criterion can be directly quantitatively measured or not. According to the categories of criteria, two different ways are proposed to normalise elementary performance expressions.

3.3.1.1 Adjusted linear utility function

For quantitative criteria, a linear utility function is defined based on the multi-attribute utility theory (MAUT) (Ogle et al., 2015), as shown in Equation 3-6.

$$\mathrm{U}(\mathrm{x_i}) = \frac{\mathrm{x_i} - \mathrm{x_i^-}}{\mathrm{x_i^+} - \mathrm{x_i^-}} \tag{3-6}$$

Where, x_i is the quantitative expression for the criterion i; x_i^- is the worst result for the criterion i, it can be considered as the minimum performance that the stakeholder can accept; x_i^+ is the best result for the criterion i, it is the ideal result that the decision maker expects. These two results, which are defined by the decision maker, represent the highest and lowest limits of the acceptable zone for the measurement of one specific evaluation criterion.

Regarding the normalised results, 1 or higher number indicates that the objective of one specific element is fully achieved ($x_i = x_i^+$) or over satisfied ($x_i > x_i^+$). In contrast, 0 shows that the performance on this element has just reached the tolerated level ($x_i = x_i^-$). There is also the possibility that the normalised result is a negative number ($x_i < x_i^-$), which means that the elementary performance is completely unsatisfied. To avoid complicating the analysis, it is considered that the normalised results vary from 0 to 1. Therefore, the mathematical equation is adjusted in the current research, as shown in Equation 3-7.

$$U(x_i) = \begin{cases} 1, & x_i \geq x_i^+ \\ \frac{x_i - x_i^-}{x_i^+ - x_i^-}, & x_i^- < x_i < x_i^+ \\ 0, & x_i \leq x_i^- \end{cases} \tag{3-7}$$

It should be noticed that this mathematical expression can only be applied to the cases where the value of the best result is bigger than that of the worst result ($x_i^+ > x_i^-$). This is the case for the dimension of value in which the higher numeric expressions mean that the more elementary values can be generated by the alternative. However, for the dimensions of cost and risk, the higher numeric results represent more negative impacts, which mean more expenses and higher instability. So, the best result is smaller than that of the worst result ($x_i^+ < x_i^-$). To make sure that the normalised results vary from 0 to 1, like the dimension of value, the normalisation equation should be adapted for these two dimensions. The normalisation mechanism for the dimension of risk is shown in Equation 3-8.

$$U(x_i) = \begin{cases} 1, & x_i \leq x_i^+ \\ \frac{x_i - x_i^+}{x_i^- - x_i^+}, & x_i^+ < x_i < x_i^- \\ 0, & x_i \geq x_i^- \end{cases} \tag{3-8}$$

The dimension of cost is different from the other two dimensions in terms of the definition of the acceptable zone for one certain evaluation element. Indeed, in an industrial project the project owner sets an initial budget (B), which is often made of different components. The project owner expects that each part of the project can be realised with a total expense not exceeding the given budget. However, in some large and complex projects, the initial budget is always exceeded with the real expense. In this context, the project owner accepts to modify the initial budget and adds additional funding. Accordingly, the limit of the acceptable zone can be adjusted in different phases of the project.

Unless the dimensions of value and risk, which have an acceptable zone from $[x_i^-, x_i^+]$, the one of the dimension of cost can be expressed as $[x_i^+, B]$ or $[x_i^+, B, x_i^-]$. The best result in practice is the one for which the project is realised with a real expense less than the initial budget. Then, depending on whether the project owner allows modifying the initial budget, the upper limit for this zone is equal to the budget or a higher amount (x_i^-), which is the maximum expense that the project owner can accept. Therefore, the normalisation mechanism for the dimension of cost is adjusted as shown in Equation 3-9 and Equation 3-10 depending if the initial budget can be revisited or not.

If the initial budget of the project cannot be exceeded:

$$U(x_i) = \begin{cases} 1, & x_i \le x_i^+ \\ \frac{B - x_i}{B - x_i^+}, & x_i^+ < x_i < B \\ 0, & x_i \ge B \end{cases} \tag{3-9}$$

If the project owner accepts to modify the budget along the project life history:

$$U(x_i) = \begin{cases} 1, & x_i \le x_i^+ \\ 0.5 + \frac{B - x_i}{2*(B - x_i^+)}, & x_i^+ < x_i < B \\ 0.5, & x_i = B \\ \frac{x_i^- - x_i}{2*(x_i^- - B)}, & B < x_i < x_i^- \\ 0, & x_i \ge x_i^- \end{cases} \tag{3-10}$$

The initial budget is usually considered as a reference point by the decision maker. In many cases, the real expenses of an industrial project are higher than the initial budget due to unexpected events. The project owner usually accepts to adjust the budget within a certain margin along the life history of the project. Therefore, the normalised expression is set to be the middle of the range [0, 1] while the cost measurement is equal to the initial budget.

3.3.1.2 Defuzzification

Comparing performance measurements represented by fuzzy numbers is a difficult task, because fuzzy numbers may overlap in many ways and it is not easy to establish whether one fuzzy number is greater or smaller than another (Molinari, 2016). Therefore, for qualitative criteria which are expressed by fuzzy numbers, it is necessary to use a defuzzification procedure to find the best non-fuzzy performance (BNP) value (Wu et al., 2009).

In the current research, the triangle fuzzy number method has been selected to transform the linguistic evaluations into quantitative expressions. The defuzzification is mainly focused on the triangular fuzzy numbers.

The "centre of area" (COA) method is practical to find out the BNP and it is not needed to bring in the preferences of any evaluators. So, it is applied to compute the BNP in the methodology. For a triangular fuzzy number (a, b, c), the BNP is given by Equation 3-11 (Vinodh et al., 2014).

$$BNP = \frac{[(c-a)+(b-a)]}{3} + a \tag{3-11}$$

In addition, the BNP value should be also normalised into numeric expressions. It varies from [0, 1] to have the same normalisation with the quantitative criteria.

3.3.2 Criteria weighting

The importance of each performance variable is subjective and it varies depending on decision makers and decision context. While aggregating the elementary performance expressions into an overall quantitative result, a ratio is assigned to each criterion to represent the relative importance of certain components within a given performance dimension.

Based on the decision maker experience, the weights for the performance elements are decided within a range [0, 1] in the current research. Higher number means higher importance the variable has. While "1" describes that the variable has the highest importance for the decision maker and "0" for the opposite direction (however, the 0 importance rarely happens in the evaluation).

Although the weights represent subjective judgements by the evaluators, the identification of these ratios should not be random. So, a method should be selected to quantitatively define the relative importance of each elementary performance expression.

In the current research, the multi-attribute utility methods (MAUMs), including AHP (Analytic Hierarchy Process), dominate other decision making techniques because of their effectiveness in ranking and task choices (Chai et al., 2013). Therefore, the AHP method, developed by Saaty (2012), is used to determine the relative importance of various criteria considered to capture the subjective judgments of the decision maker.

AHP uses pairwise comparisons along with expert judgments to handle the measurement of qualitative or intangible attributes. The evaluators define the relevant importance through one single numerical number for each pair of evaluation criteria. As shown in Equation 3-12, the normalised weights for each criteria can be calculated using the method suggested by Saaty (2012).

$$w_j = \left(\sum_{j=1}^{j} \left(\frac{a_{jk}}{\sum_{k=1}^{k} a_{jk}}\right)\right)/k, \quad \sum_{j=1}^{j} w_j = 1 \tag{3-12}$$

Where, w_j is the weight of criterion j, j is the index number of rows and k is the index number of columns. a_{jk} is the relative scale between two criteria and it is defended by the decision maker according to his or her knowledge and preference.

Furthermore, the consistency of judgments used in pairwise comparisons is very important. Decisions should not be based on judgments with low consistency because they would appear to be random (Ordoobadi, 2013). The AHP measures the overall consistency of judgments by means of consistency ratio (CR). The consistency ratio can be calculated by means of Equation 3-13 and Equation 3-14, which are suggested by Saaty (2012).

$$CR = CI/RI \tag{3-13}$$

$$\mathrm{CI} = \frac{\lambda_{max} - n}{n-1} \tag{3-14}$$

Where, CI is the consistency index. RI is the average random consistency index for different matrix orders based on the experience data (Table 3-8) (Peláez & Lamata, 2003). λ_{max} is the maximum eigenvalue of the matrix and n is the size of the matrix.

Table 3-8. Values of the random index for different matrix orders

n	1-2	3	4	5	6	7
RI	0	0.58	0.90	1.12	1.24	1.32

According to Saaty (2012), the value of this ratio should be less than 10 %. Otherwise, the judgments may be somewhat random and must be revised.

For example, if the value of a Ph.D. project can be estimated by means of the following three evaluation criteria: the duration of the project (C1), the knowledge acquired in a specific field (C2) and the scientific contribution (C3). The results of the criteria weighting is shown in Table 3-9.

Table 3-9. Example of criteria weighting for the Ph.D. project

	C1	C2	C3	Normalised weight
C1	1	1/3	5	0.283
C2	3	1	7	0.643
C3	1/5	1/7	1	0.074

With $\lambda_{max} = 3.054, n = 3$, then$\mathrm{CI} = 0.027$, RI = 0.58 and CR = 0.047. It means that the judgments in the illustrated matrix are considered as not random.

3.3.3 Aggregation operations

Once the elementary performances are available, the next step concerns the choice of the operator for the aggregation. This operation is executed by following the opposite direction of the breakdown structure. It means that the same operation should be duplicated from the lowest to highest level in the hierarchical tree structure.

3.3.3.1 Weighted arithmetic sum

The most frequently used aggregation method is the weighted arithmetic sum (WAS). The overall value, cost and risk are aggregated with Equation 3-15.

$$V_k = \sum_{i=1}^{n} w_{ik} \times V_{ik}, \quad \sum_{i=1}^{n} w_{ik} = 1 \tag{3-15}$$

Where, V_k is the global value of one axis k (value or risk), V_{ik} is the elementary measure of criterion i in the axis k, w_{ik} is the weight of criterion i in the axis k according to the preference of a decision maker and n is the number of performance criteria in the same dimension.

However, it should be noticed that cost variables are always measured and expressed by monetary terms which can be directly applied to the aggregation operations. Unlike value and risk expressions that may contain quite a lot of subjective judgements, elementary cost expressions are almost not influenced by stakeholder preferences. Therefore, it is considered that different cost variables may have less difference in terms of the relative importance while generating an aggregate result (it means that the weight for each elementary cost expression is considered as 1 in aggregation operation). The overall cost of each level in the breakdown structure is accumulated as the sum of its components. For the purpose of decision support with comprehensive performance expression, the cost expression should be normalised into a number between [0, 1] like the value and risk dimensions.

Furthermore, if the breakdown structure is developed based on the process modelling approach, for instance with IDEF3, the logical connectors (represented by junction boxes) also influence the aggregation computation of different performance dimensions.

- With the AND junction, the aggregation computation varies with different performance dimensions. The overall value cost and risk is aggregated with Equation 3-15.
- With the OR junction, the aggregated value will be the highest elementary expression in the alternative branches, as shown in Equation 3-16.

$$Ag\ (V_k)\ =\ Max(ag(w_{k1}, V_{k1}), \cdots, (w_{ki}, V_{ki})) \tag{3-16}$$

The overall cost or risk is the element with the lowest expression, because it is considered that the lowest normalised quantitative expression represents the highest cost or risk. So, the aggregation is generated by Equation 3-17.

$$Ag\ (V_k)\ =\ Min(ag(w_{k1}, V_{k1}), \cdots, (w_{ki}, V_{ki})) \tag{3-17}$$

The WAS aggregation operator provides an efficient way to get the overall performance measure. However, in this method, all criteria are independent of one another and do not influence each other, which is not always the case in real practice. To overcome this disadvantage, the Choquet integral-based operators are used as another aggregation operator in the proposed methodology.

3.3.3.2 Choquet integral-based aggregation

Choquet integral-based operators (Labreuche & Grabisch, 2003) belongs to a very important class of information aggregation operators which have had a wide variety of applications in the last years (Llamazares, 2015). Particularly, the 2-additive Choquet integral, that considers only pairwise interactions, is defined by two main parameters: Shapley parameters and interaction parameters.

- The Shapley parameters v_i: they must satisfy $\sum_{i=1}^{n} v_i = 1$ and their objective is to quantify the weights of each performance criterion;

- The interaction parameters I_{ij}: for any pair of performance criteria, they range in [-1, 1]. A positive value means a positive interaction, a negative value means a negative interaction and a null value means that no interaction exists.

The aggregation function is given by Equation 3-18:

$$\mathrm{CI_g}(p_1, p_2, \cdots, p_n) = \sum_{i=1}^{n} v_i p_i - \frac{1}{2}\sum_{i=1}^{n} I_{ij} \left|p_i - p_j\right| \tag{3-18}$$

With the property that:

$$\left(v_i - \frac{1}{2}\sum_{j=1}^{n}\left|I_{ij}\right|\right) \geq 0,\ \ \forall\, i \in [1, n], i \neq j \; and \; \sum_{i=1}^{n} \boldsymbol{v_i} = \mathbf{1}$$

Where, v_i are the so-called Shapley parameters that represent the relative importance of each criterion; I_{ij} are called interaction parameters to show the interactions between each pair of criteria. The meanings of v_i and I_{ij} provide explanations to the decision maker on how these parameters influence the aggregated measures. It is considered that the weights generated through the pair-wised comparison can be used as Shapley parameters. And the interaction parameters are identified through the order of priority among different elements defined by the evaluator.

The elementary performance expressions for the dimension of cost are objective and cumulative. Therefore, in most cases, it is considered that the weight of each elementary cost is constant as "1" for all elements, hence, the aggregated cost of each level is calculated by the average of all elementary costs. In this context, the two selected aggregation operators are applied to compute the overall value and risk of a project. However, in some particular decision problems, some elementary costs are more important than other components for the decision makers. Then, the elementary measures of the three performance dimensions are aggregated by following the same operations.

3.4 Visualised decision support

To integrate the decision maker preferences in a visualised approach, different zones of aversion, acceptability and desirability should be determined for each CVR dimension by the decision maker himself in a particular decision context. This will make the comparison and ranking of different scenarios more effective. Therefore, based on the preference of the decision makers, the evaluator should firstly define different thresholds within a range [0, 1] for identifying the boundaries between these zones by dimension. Thus, the next step is to place the aggregated results in the space in order to make easier decision making. This approach was suggested in the thesis of Shah (2012) and is further elaborated in this document.

3.4.1 Definition of preference zones

The aggregation operation provides the decision maker with a single overall quantitative expression within a range [0, 1] for each performance dimension. Bigger numeric result represents better performance in a specific CVR dimensions. To ease the evaluation, the range [0, 1] should be divided into different zones, which are defined based on the evaluator preference.

Shah (2012) proposed to define three zones *(value aversion/indifference, value tolerance/acceptable and value desirability)* for the axis of value and three zones *(risk appetite, risk tolerance and risk intolerance)* for the dimension of risk. In a similar way, it is also considered that each dimension can be divided into three zones (desired, acceptable and intolerable) as shown in Figure 3-14.

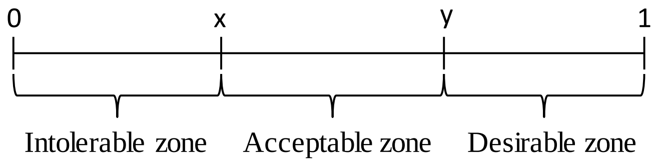


Figure 3-14. Zones for performance dimensions

The variables x and y are defined by the evaluator to show the critical points of different zones in the range [0, 1]. They reflect the subjective evaluator preference and expectation while considering the performance of an alternative in a decision problem. Regarding the signification of each axis, the names of each zone are slightly adjusted in each dimension.

The dimension of cost is divided into three parts: unacceptable cost, tolerable cost and desired cost. The unacceptable cost zone means that the project expense is out of the range that the decision maker can accept. The tolerable cost zone refers to a higher expense than expected, but it can still be accepted by the decision maker. The desired cost zone means that the project can be performed with a total expense lower than initially expected or planned.

The dimension of value is divided into insufficient, acceptable and desired value zones. The insufficient value zone indicates that the project cannot generate sufficient value for the stakeholder. The acceptable value zone indicates that the outcome of the project may satisfy the essential requirements of the stakeholders and that it can be accepted by them although more value was expected. The desired value zone indicates that the outcome of the project fully satisfies the stakeholder or even exceeds the expectations.

The dimension of risk is divided into unacceptable, tolerable and desirable risk zones. The unacceptable zone means that the project is too risky to be accepted and it has high probability to fail. The tolerable risk zone specifies the maximum range of risk that the stakeholder is willing to take. The desirable risk zone indicates that the project risk is limited or that it is even lower that the stakeholder expected.

To quantitatively determine the variables x and y, it is proposed to define a target limit for each zone as well as the degree of variation. Regarding the example of the Ph.D. programme, if the predefined scholarship for the whole project is X euros (it can be considered as the initial budget), the evaluator may consider that the target limit for an acceptable cost of a Ph.D. project is from X to 1.5X euros (which means x=1.5X and y=X, because the axis ranges from the worst to the ideal situations).

These results should be normalised to fit within the numeric scale [0, 1] in order to be consistent with the normalised overall performance expressions. Therefore, the lower and upper bounds should be set to represent the maximum expense in the worst situation and the minimum expense in the ideal case. They are corresponding to 0 and 1 on the axis of cost in the graphic. For example, if the maximum and minimum project expenses are assumed to be 2X and 0.8X, the numeric expressions 1.5X and X can be normalised using Equation 3-3 of this chapter. Therefore, the unacceptable cost zone is [0, 0.42], the tolerable cost zone is [0.42, 0.83] and the desired cost zone is [0.83, 1].

However, for the dimensions of value and risk, the numeric expressions of x and y should be directly defined as numbers between 0 and 1 based on the evaluator objective. Because unlike the dimension of cost, which is only expressed by monetary terms and the overall cost can be presented by either amount of money or a normalised result, the axes of value and risk contain elements with different units and the overall value and risk can only be expressed by normalised results.

However, it should be noticed that the essential objective of this visualisation tool is to make easier the decision while selecting among or comparing different performance expressions. So, the proposed definition of the preference zones is only a guide for the decision makers to transfer their linguistic preferences into quantitative expressions.

Based on the specific decision context and the decision maker preference, the numeric expression for each dimension can be modified. For the dimensions of cost and risk, the meaning of the range [0, 1] can be inverted. The higher number shows that the alternative is more costly and risky. In addition, one axis could be divided into two preference zones instead of three if the decision maker feels that only one critical point can be identified for the dimension.

3.4.2 Graph with performance dimensions

Once the preference zones for each performance dimension have been defined, the following step is to introduce a visualisation approach to display the overall performance of each alternative for easy comparison among different solutions.

Based on the particular decision context and the evaluator convenience, the decision maker can decide to work with 2-axis graphs, such as cost-value graphs, value-risk graphs or cost-risk graphs, if two dimensions are more important for the decision maker. Similarly, the decision maker can choose to work with all the three dimensions of cost, value and risk at once, if an overall image is more efficient to support the decision making process.

3.4.2.1 2D Graph

The 2D graph represents the overall performance in terms of the two most important dimensions selected by the decision maker. Based on the proposed value-risk graph (Shah, 2012; Vernadat et al., 2013), a new version of the 2D graph is proposed in the current research, as show in Figure 3-15.

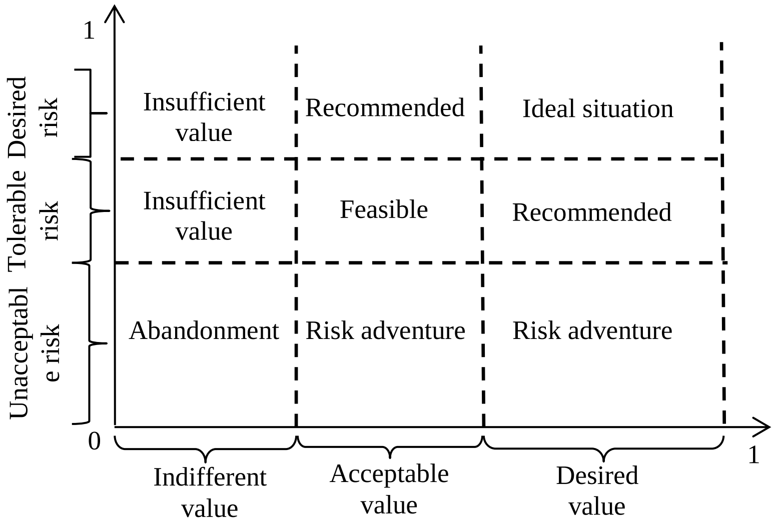


Figure 3-15. Value-risk graph

The 2D graph is made of two parts: (1) different preference zones for each axis and (2) different evaluation zones in the graph. Once the position of one specific alternative is identified in the graph, the evaluator can directly locate the performance degree regarding the selected performance dimensions and its relevant position for decision making.

Similarly, cost-value graphs and cost-risk graphs can be developed and shown in Figure 3-16 and Figure 3-17.

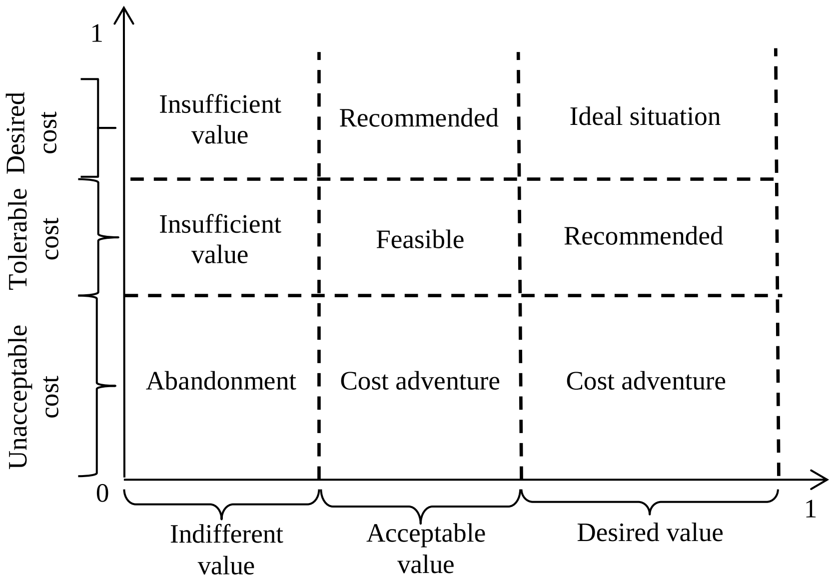


Figure 3-16. Cost-value graph

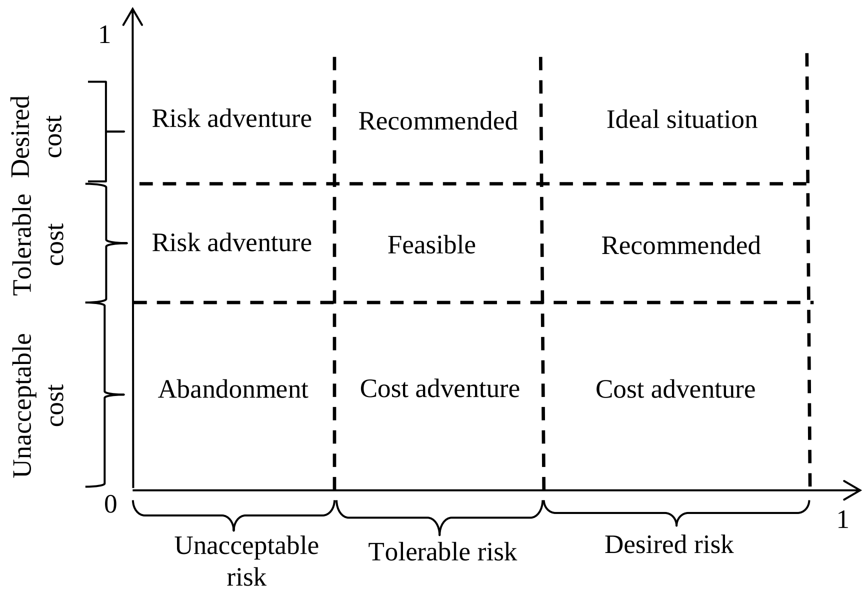


Figure 3-17. Cost-risk graph

As presented in Chapter II, in some particular cases some other performance dimensions other than cost, value and risk can be considered as extremely important for the project success (for example, project duration for a fashion design project). In other situations, one of the dimensions of cost, value and risk has much more influence than the others on the decision making (for example, cost for a large civil engineering project and risk for a nuclear plant construction project). Therefore, the two axes in the graph are not limited to cost, value or risk. According to the specific decision context, it can be adapted to cost-time, risk-time or value-time graph.

3.4.2.2 3D Graph

With the 3D graph, the overall cost, value and risk of one decision alternative or more can be presented in a cost-value-risk space to assist the decision maker to evaluate the performance of different decision alternatives denoted P(an) (with n=1,2,…n) (for example, different solutions or candidate projects) according to their preferences (Figure 3-18). It can be used to evaluate the opportunity of several decision alternatives while defining the best solution for a new project.

In addition, in the case of project monitoring, the evaluator focuses on the evolution of one specific alternative overall performance along the project life history. In this context, the quantitative results of the global performance at different moments denoted P(tn) (with n=1,2,…n) can also be presented in the same 3D graph (Figure 3-19). With the project trajectory, the variation of the overall cost, value and risk at different moments can be evaluated in order to help the decision maker to steer the project in progress.

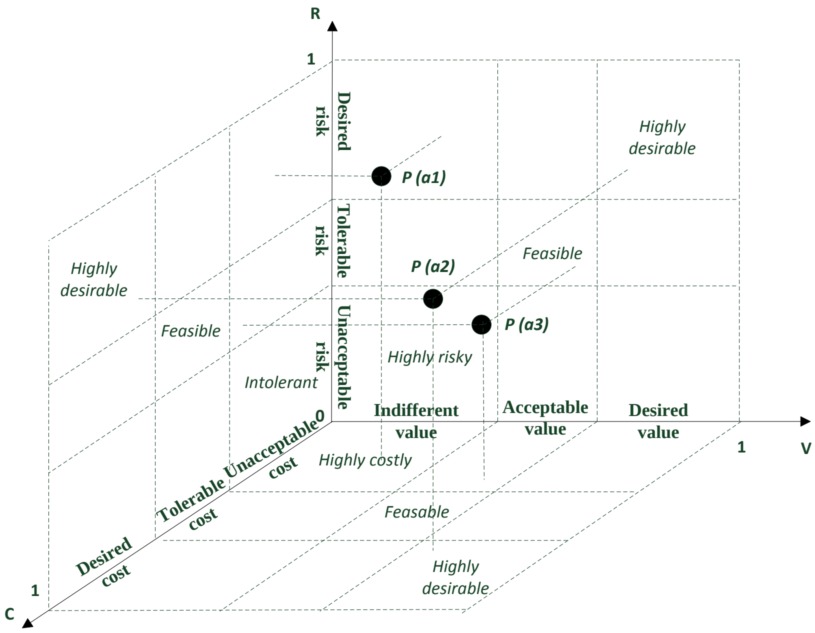


Figure 3-18. Performance of different scenarios in a cost-value-risk graph

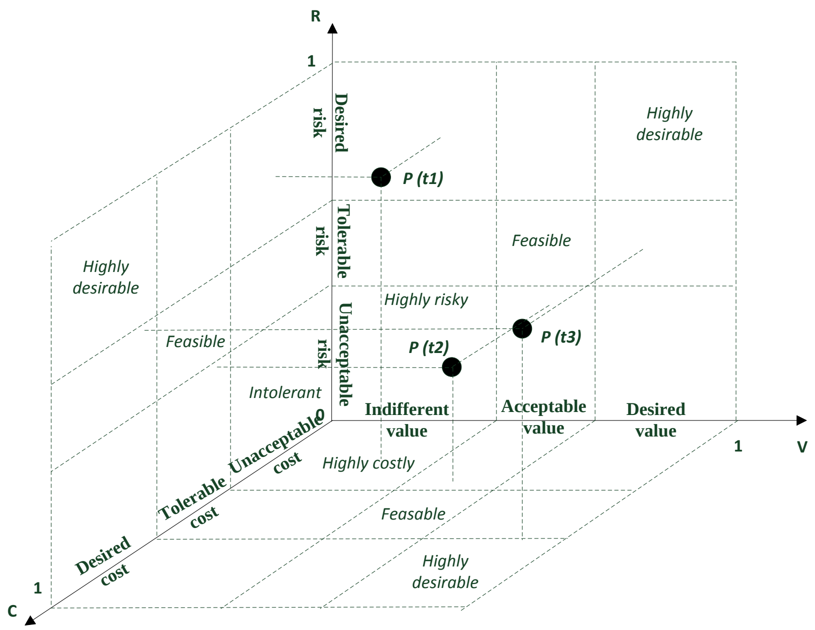


Figure 3-19. Performance at different moments in cost-value-risk graph

3.4.3 Discussion: performance variation

The suggested visualisation tool is proposed to help the evaluator in a decision making problem to visually evaluate the overall performance compared to the predefined preferences. This presentation is based on the performance measurement of one specific decision alternative with one particular evaluation period.

However, it should be noticed that the overall performance expressions at the selected evaluation period may not be accurate enough for the decision maker to compare different decision alternatives. Better performance results can only prove that the selected decision alternative is closer to the evaluator objective at the time of evaluation, but it cannot assume that this alternative can be always the most performed solution in the following evaluation periods along the project life history. The concept of "performance variation" should be introduced to assess the evolution of performance over time. Therefore, it is necessary to introduce another term to represent the variation of the performance for a certain decision alternative.

In the current research, it is considered that the performance expression for decision support should include two parts: (1) performance measurement for one specific time interval and (2) gap of performance variations (GA). The former is the overall value, cost and risk, which are obtained from the aggregation computation. The latter is the difference between two overall expressions for one specific alternative in terms of one certain performance dimension over the relevant time interval along a project or process life history.

The first term is the deliverable of the proposed methodology. The second term should be computed based on different overall performance expressions. For this purpose, a set of concepts are proposed. The first is the performance variation as shown in Equation 3-19.

$$VA_c = \left(\frac{C_i - C_j}{t_i - t_j}\right), VA_v = \left(\frac{V_i - V_j}{t_i - t_j}\right), VA_r = \left(\frac{R_i - R_j}{t_i - t_j}\right) \tag{3-19}$$

Where, $VA_c, VA_v\ and\ VA_r$ are the performance variations in terms of cost, value and risk. $t_i\ and\ t_j$ are two moments along the project life history. $C_i - C_j, V_i - V_j\ and R_i - R_j$ are the differences between two performance measures of the same dimension at the selected moments. For most cases, it is supposed that the numeric expressions of the initial time, cost, value and risk in a decision making problem equal to 0, that is, the results of these elements $t_0, C_0,\ V_0, R_0$ are set to be 0.

According to the type of overall performance expression, it can be categorised in two types: desired and estimated variation. The desired variation (DV) is the difference between (1) the desired quantitative measures that are predefined by the decision maker and (2) the performance expression at the initial moment over the relevant time interval. The mathematic expressions are shown in Equation 3-20.

$$DV_c = \left(\frac{C_d - C_0}{T - t_0}\right) = \frac{C_d}{T}, DV_v = \left(\frac{V_d - V_0}{T - t_0}\right) = \frac{V_d}{T}, DV_r = \left(\frac{R_i - R_0}{t_i - t_0}\right) = \frac{R_d}{T} \tag{3-20}$$

Similarly, the estimated variation (EV) is the difference between (1) the performance measures, which are the deliverables of the aggregation computation, and (2) the performance expression at the initial moment over the relevant time interval, as shown in Equation 3-21.

$$EV_c = \left(\frac{C_i - C_0}{t_i - t_0}\right) = \frac{C_i}{t_i}, EV_v = \left(\frac{V_i - V_0}{t_i - t_0}\right) = \frac{V_i}{t_i}, EV_r = \left(\frac{R_i - R_0}{t_i - t_0}\right) = \frac{R_i}{t_i} \tag{3-21}$$

The estimated variation should be adjusted, because the performance measures are influenced by the decision maker subjective judgment. Therefore, the estimated variation after adjustment (EVA) is defined to take into consideration the random events which can influence the evaluation of the overall expression of one specific performance dimension along the life history of the project or process. The mathematic expression of the term EVA is presented in Equation 3-22.

$$EVA = EV \times \varepsilon \times C \tag{3-22}$$

Where, ε is a random number that represents the happening of random events. C is a constant number between 0 and 1, which represents the degree of variance of one particular performance dimension according to the decision maker estimation.

To describe the uncertainty of the overall performance in one specific dimension, the term gap of variation (GA) is proposed. It is defined as the absolute value of the difference between desired variation and the maximum absolute value of estimated variation, as shown in Equation 3-23.

$$GA = |DV - \max|EVA|| = |DV - \max|EV \times \varepsilon \times C|| \tag{3-23}$$

Finally, the overall performance expression for decision support can be adjusted as shown in Equation 3-24.

$$P(A) = \{(C, GA_c), \left(V,\ GA_v\ \right), (R, GA_r)\} \tag{3-24}$$

In some cases, the decision maker needs to predict future performance of the project or process in order to improve the management control and generate more effective action plans for future steps. Hereby, the proposed terms can also be used to forecast the overall performance after a considered time interval. The predicted performance can be expressed as shown in Equation 3-25.

$$P(A') = P(A) \times (1 + EVA) \tag{3-25}$$

Based on these definitions, a process for decision support can be proposed as shown in Figure 3-20.

Through the graphic presentation, the decision maker evaluates whether the overall performance is preferred. If there is no preferred solution, the action plan should be modified and a new performance measurement should be generated. If the answer is positive, the following step aims to evaluate the gap of EVA to ensure this alternative can have a stable performance in the future phases of the project. With an acceptable EVA, the alternative can be considered as a solution with reliable performance along the life history of a project. Otherwise, it means that even if the selected decision alternative has the preferred overall performance at the moment of evaluation, there may exist strong possibility that the performance possesses large variation in the future phases of the project.

It is a fairly complex subject to estimate the deviation and liability of the overall performance expressions. The proposed operations are only an extension of the decision support phase. Further studies should be applied to accomplish this requirement. Therefore, it can be considered as a research direction for future improvement of the methodology.

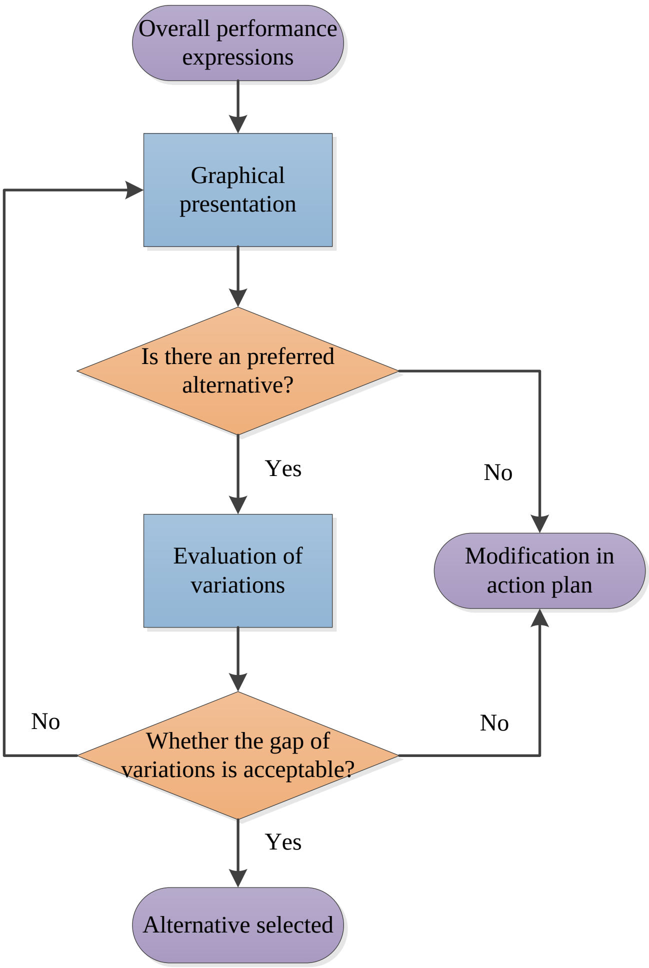


Figure 3-20. Process for decision support

3.5 Conclusions

The proposed performance evaluation methodology is made of four main phases: (1) identification of performance elements, (2) performance measurements and quantification, (3) aggregation of elementary measurement and (4) visualised decision support. Each phase relies on the use of a set of tools and techniques to generate the expected deliverables.

In this chapter, the main processes and the detailed operations of each step have been presented with a summary of the main methods and tools that can be applied in today's industrial practice. However, there is no universal combination of tools and techniques for all kinds of decision situations. The selection of appropriate solutions depends on the particular project context and decision problems, as well as the preference of the evaluator. The objective of this section was to provide a guide helping the evaluator to choose the appropriate tools and methods regarding a specific situation while applying the proposed performance evaluation methodology. In addition, different elementary costs and risks in the context of project management (as shown in Appendix A and Appendix B) have been proposed to help the evaluator to efficiently identify the cost and risk variables regarding a particular decision context.

It is considered that the proposed performance evaluation methodology can be applied to different kinds of decision projects or problems in different industrial contexts. Besides the example of the Ph.D. project that is presented to facilitate the understanding of the theoretical description given in this chapter, some cases studies in other industrial contexts regarding opportunity evaluation of a new project and monitoring of an ongoing project will be presented in the following chapter to apply and illustrate the proposed methodology.

CHAPTER IV: BCVR PERFORMANCE EVALUATION: EXPERIMENTAL APPLICATIONS

The foundations and the theoretical elements of the proposed BCVR methodology, including the essential concepts, overall methodological framework and supporting methods and tools, have been presented in the previous chapters. It is claimed that this methodology can be applied to the following types of problems: (1) decision support based on benefit, cost, value and/or risk evaluation, this could be *a priori* analysis such as opportunity assessment of different alternatives while selecting the most appropriate one at the preliminary phase of an industrial system or *de facto* analysis such as decision making; (2) performance evaluation at any stage of an industrial system, process or project (*a priori*, *de facto* or *a posteriori*) and (3) monitoring and control of an ongoing industrial project requiring performance evaluation steps at different phases along the life history of the project. Taking into account the discussion given at the end of the Chapter III, the overall performance of future states (i.e. *a priori* evaluation) could be predicted on the basis of two elements: (1) existing overall performance expression at a certain evaluation period and (2) estimated variation or trend after adjustment.

In this thesis report, the application of the proposed methodology will be illustrated for these types of problems by means of three case studies dealing with different decision contexts. The three case studies analysed in this chapter are: (1) supplier selection, (2) building construction project implementation and (3) monitoring of an IT development project. The first two cases illustrate the application of the methodology in terms of decision support, first on a type of problems requiring analysis on only one dimension of the BCVR approach and, then, using all the dimensions with a mix of numeric and linguistic variables. The third case is an application of the BVCR methodology to various steps of the management of an IT project. It illustrates the second type of problems (performance evaluation) and the third one (project monitoring). The global structure of Chapter IV is summarised by Figure 4-1.

Applications to decision support and project management

	Problem 1: Decision support	Problem 2: Performance evaluation	Problem 3: Project monitoring
Case 1: Supplier selection	√		
Case 2: Construction projects implementation	√		
Case 3: IT development project		√	√

Figure 4-1. Global structure of Chapter IV

Case 1 deals with risk evaluation in a supplier selection process. The objective of this case study is to apply and verify the proposed methodology in a decision context with limited complexity for the analysis.

Case 2 refers to the application of the methodology to construction projects during the implementation stage. The performance evaluation results are used to compare different projects in order to decide the priority order in the implementation phase.

Case 3 concerns the monitoring and control of a real IT development project which faced several management problems in its execution. The objective is to demonstrate the usefulness of performance evaluation to support management decisions of an industrial project.

These three cases mostly deal with the fields of decision making and project management. Considering in addition the application to manufacturing processes that was discussed by Shah (2012) in his doctoral thesis, we can claim that the proposed methodology can also be used in process management.

4.1 Case study 1: Risk evaluation in supplier selection process

In this case, the proposed performance evaluation methodology is applied to evaluation in a supplier selection process using one main criterion: risk. The overall risk of each candidate supplier is evaluated throughout the whole process of supplier selection to help the decision maker when comparing several alternatives.

4.1.1 Background

With more complex services and products to be offered as well as shorter delivery times required by customers, a wide range of companies apply the concepts of total quality management (TQM) and just in time (JIT) and they more heavily rely on outsourcing through collaboration with other organisations. Furthermore, companies spend a large amount of their revenue to purchase goods or services. In this context, company success largely depends on the interactions with its external suppliers.

Supplier selection is the process by which an organisation identifies, evaluates and contracts suppliers. This process usually engages a large amount of the company’s financial resources. Therefore, the company expects significant profit from contracting suppliers offering high value with acceptable cost and tolerable risk. Thus, the selection of the most appropriate supplier is always an essential decision problem in most logistic projects.

Usually, companies select suppliers based on the relative importance of different attributes, such as quality, price, flexibility and delivery time, which can be summarised within the CVR performance dimensions. In terms of cost, the unit price of components or of raw materials is a typical evaluation criterion. Other components such as payment terms, cash discount, ordering cost, carrying cost, logistics costs and maintenance costs could also be taken into consideration. The value and risk dimensions mainly refer to the quality, reliability and flexibility of suppliers. The supplier must demonstrate that it has the capabilities to consistently meet the specified requirements with the capacity to back up products by providing good services when needed. In addition, the supplier should be reliable in characteristics such as delivery lead-time and on-time delivery rate. Otherwise, production in the buying company (i.e. the contractor) may have to be interrupted due to shortage of raw materials or components. Furthermore, the supplier should be flexible in case of changing the order. Finally, to avoid potential competition between the supplier and the contractor, it is also important that the supplier has the willingness to share technologies and information.

In this case study, the problem is to select a supplier from three candidate suppliers. This supplier will be added to the supply chain of the contractor (e.g. a company manufacturing sub-assembly parts for the automotive industry). The three candidate suppliers have the capabilities to produce the parts according to imposed technical requirements and can offer them at similar prices. Value and cost are therefore considered as non-discriminant factors in this decision making problem.

Based on this description, it can be considered that the selection of the potential supplier can be mainly evaluated on the basis of one dimension: risk. In this context, the case study mainly focuses on risk evaluation during the process. The objective of the case study is to demonstrate that the BCVR approach can (1) be used as a decision support tool in supplier selection in the preliminary phase of a project and (2) does not necessarily require the evaluator to consider all dimensions together.

4.1.2 Identification phase

According to the synopsis of the BCVR methodology presented in Chapter II, the analysis starts with the identification phase in order to identify stakeholders and establish the list of objectives and evaluation variables.

The main stakeholder involved in this case study appears to be the contractor (for instance, represented by its procurement manager, procurement agent or contract manager) who identifies, evaluates and contracts the suppliers. The contractor must define and measure what “potential risks” means for the contracting organisation and must execute procurement decisions accordingly. To identify the main potential risks, the contractor must get in touch with the technical, legal and operations experts of the contracting company and act as an expert negotiator and coordinator across many internal and external parties.

The procurement decisions are always carried out at the early stages of a project. Hence, the evaluation period for this case study refers to the initialisation phase of a project (as explained in Chapter II, Section 2.2).

The main benefits of selecting the proper supplier can be summarised as: (1) purchasing price reduction on the long term, (2) supplier knowledge improvement with better understanding of contractor’s demands through a close collaboration and (3) internal cost reduction in the contracting company because of lower inventory levels, scrap rate and inspection costs.

The risk variables can in this case be identified both by means of activity modelling and objectives modelling approaches to develop the breakdown structure of the risk evaluation.

4.1.2.1 Activity modelling

Although the supplier selection process may vary from company to company and although a variety of different approaches are used to evaluate and select suppliers, a typical supplier evaluation and selection process can be linearly defined with the following critical steps: (1) acknowledge the need for outsourcing, (2) determine elements (criteria, method and approach) for outsourcing, (3) identify suppliers, (4) solicit information from suppliers, (5) set evaluation methodology and evaluate suppliers and (6) negotiate and sign contract with the selected supplier.

This generic process can be modelled using an enterprise modelling approach. Figure 4-2 shows the supplier selection process modelled with the IDEF3 modelling language.

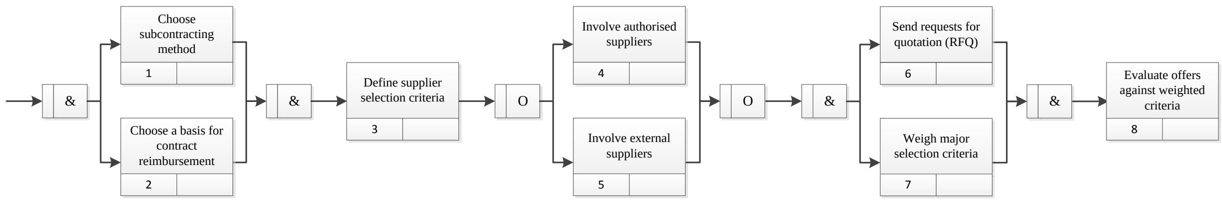


Figure 4-2. IDEF3 supplier selection process model

The process starts with the selection of the subcontracting method and the basis for contract reimbursement which is decided by the contracting company. As soon as these have been decided, the supplier selection criteria are defined. Then, either authorised suppliers or external suppliers are involved as potential suppliers. An authorised (approved) supplier is a qualified supplier that is approved by a company as one from whom to regularly procure materials or services. Many companies have an approved supplier list (ASL) to which a qualified supplier is then added. Once approved, a supplier may be revaluated on a periodic basis. An external supplier is a new supplier that is not yet registered in the ASL and it usually represents more uncertainty to the buying company.

After this step, the contracting company sends requests for quotation (RFQ) to potential suppliers. A RFQ is an invitation sent to potential suppliers to bid for providing the specific products (i.e. automotive parts). The bid offer involves not only the price per item, but also information such as payment terms, quality level per item or contract duration. Meanwhile, the major selection criteria are weighed. At last, offers are compared and evaluated against weighted criteria in order to identify the most appropriate supplier.

Each activity of the process can generate elementary risks. Its performance can be expressed through related elementary objectives. Therefore, the IDEF3 model is considered as the basis for developing activity-based objective identification for risk evaluation. To limit the complexity of the final objective breakdown structure, it is recommended to as much as possible create only one elementary objective for each activity. Table 4-1 provides a match between IDEF3 model steps (UOBs) and the corresponding elementary objectives for risk evaluation.

Table 4-1. IDEF3 model steps and corresponding elementary objectives for case study 1

IDEF3 step labels	Elementary objectives
Choose subcontracting method	Avoid uncompleted definitions about final outcome
Choose a basis for contract reimbursement	Allocate enough time for contract reimbursement
Define supplier selection criteria	Ensure the selected criteria should be comprehensive and suitable for the decision context
Involve authorised suppliers	Increase flexibility to respond to change
Involve external suppliers	Avoid instable financial and technical situations of the supplier
Send requests for quotation	Avoid imprecision of specification about the deliverables
Weigh major selection criteria	Minimise errors in weight definition
Evaluate offers against weighed criteria	Minimise errors in analysis

Activity modelling provides an *ad hoc* method for objective identification based on the process model. Each elementary objective can be considered as a risk variable in the overall performance expression framework. Once the evaluation criteria for each elementary objective have been identified, the IDEF3 model can be transformed into a breakdown structure for risk evaluation.

However, this breakdown structure is not necessarily the most appropriate and complete decision alternative regarding all important evaluation elements in the decision problem. Therefore, another analysis based on objectives modelling should be developed to complete the hierarchical structure.

4.1.2.2 Objectives modelling

According to the value focused thinking (VFT) method, the fundamental objective for risk evaluation in the supplier selection process can be described as "minimise risk of choosing an inadequate supplier". It can be further explained by several main components which are considered as the means objectives. They are summarised as:

- Minimise risk of supplier inability to meet specifications.
- Minimise risk of insufficient coordination with supplier.
- Minimise risk of supplier financial instability.
- Minimise risk of non-standardised workflow in communication with supplier.
- Minimise risk of dependence on supplier.
- Minimise risk of supplier becoming a potential competitor of the contractor.

The word "minimise" in these expressions indicates that these objectives are expressed from the point view of operations research which always focuses on the optimal results.

The VFT method allows the evaluator to generate better alternatives for any decision problems. However, compared to activity modelling, the objectives modelling structure has limited capacity to reflect the hierarchical relations among different elementary objectives. Therefore, these two modelling structures should be consistently synchronised to integrate both advantages in the final hierarchical structure. This synchronisation can be developed with the consideration that matching at elementary levels of both modelling structures exists. Table 4-2 shows the relations among elements of both structures.

Table 4-2. Synchronisation of modelling structures for case study 1

Activity-based objectives \ VFT means objectives	Minimise risk of supplier inability to conform to specifications	Minimise risk of insufficient coordination with supplier	Minimise risk of supplier financial instability	Minimise risk of non-standardised workflow in communication with supplier	Minimise risk of dependence on supplier	Minimise risk of supplier becoming a potential competitor
Avoid uncompleted definitions about final outcome	√	-	-	-	√	√
Allocate enough time for contract reimbursement	-	-	-	-	√	-
Make sure that the selected criteria are comprehensive and suitable for the decision context	√	-	√	-	√	√
Increase flexibility to respond to change	√	√	√	√	√	√
Avoid instable financial and technical situations of the supplier	√	√	√	√	√	√
Avoid imprecision of specification about the deliverables	√	√	√	√	-	-
Minimise errors in weight definition	√	-	√	-	√	√
Minimise errors in analysis	√	√	√	√	√	√

Based on the associations among elementary objectives that are generated through activity and objective modelling, the IDEF3 model can be transformed into the final hierarchical structure for risk evaluation of the supplier selection process.

4.1.2.3 Breakdown structure development

The breakdown structure development is split into the following steps:

- Step 1: Basic structure development

  The selection process is divided into several segments to ease the evaluation. One segment is defined as the UOB(s) between each two successive junctions. Then, each segment is considered to be associated with a means objective that directly supports the fundamental objective of the process, as shown in Figure 4-3.

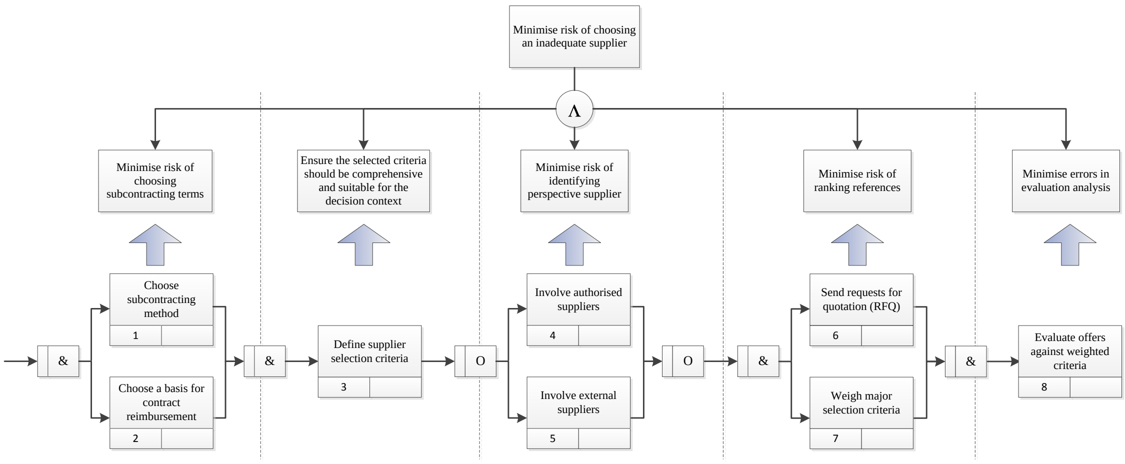


Figure 4-3. Basic structure with the process modelling result for case study 1

For segments that contain more than one UOB, the relevant branches can be further developed with the associated elementary objectives. The relations between the elementary objectives within the same branch are indicated in the IDEF3 model. The adjusted basic structure is shown in Figure 4-4. At the end of this step, the number of the basic objectives (which do not have other objectives at the lower lever) is the same as that of the UOB in the IDEF3 model.

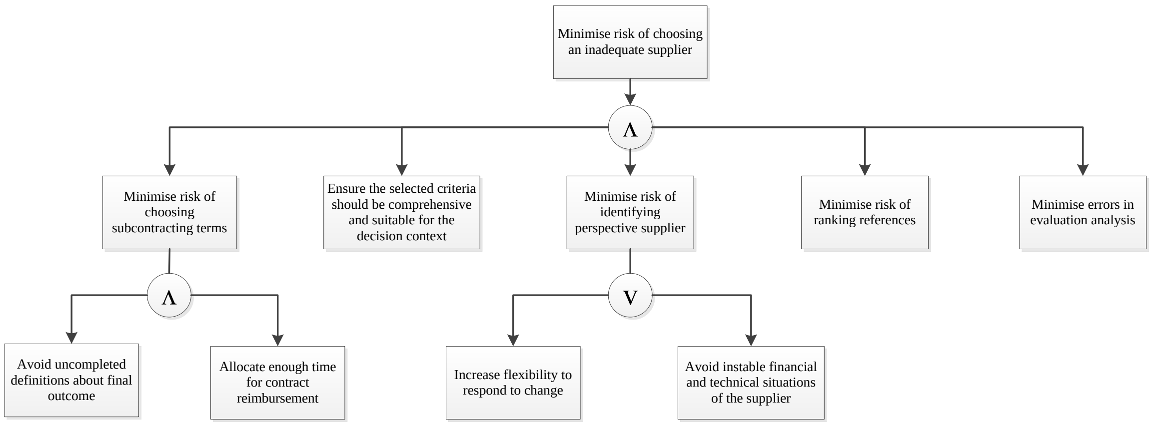


Figure 4-4. Adjusted basic structure for case study 1

The basic structure only contains the activity-based objectives. The means objectives generated by VFT should be also involved in the breakdown structure to complete the analysis.

- Step 2: Complete structure development
  Each activity-based objective is associated with several VFT means objectives. Based on the synchronisation result with these elementary objectives as shown in Table 4-2, the complete breakdown is developed as shown in Figure 4-5. Since the focus is more on the evaluation activity, the risk assessment in this case study mainly concerns the risk in evaluation analysis. The other branches are not further analysed in the following analysis.

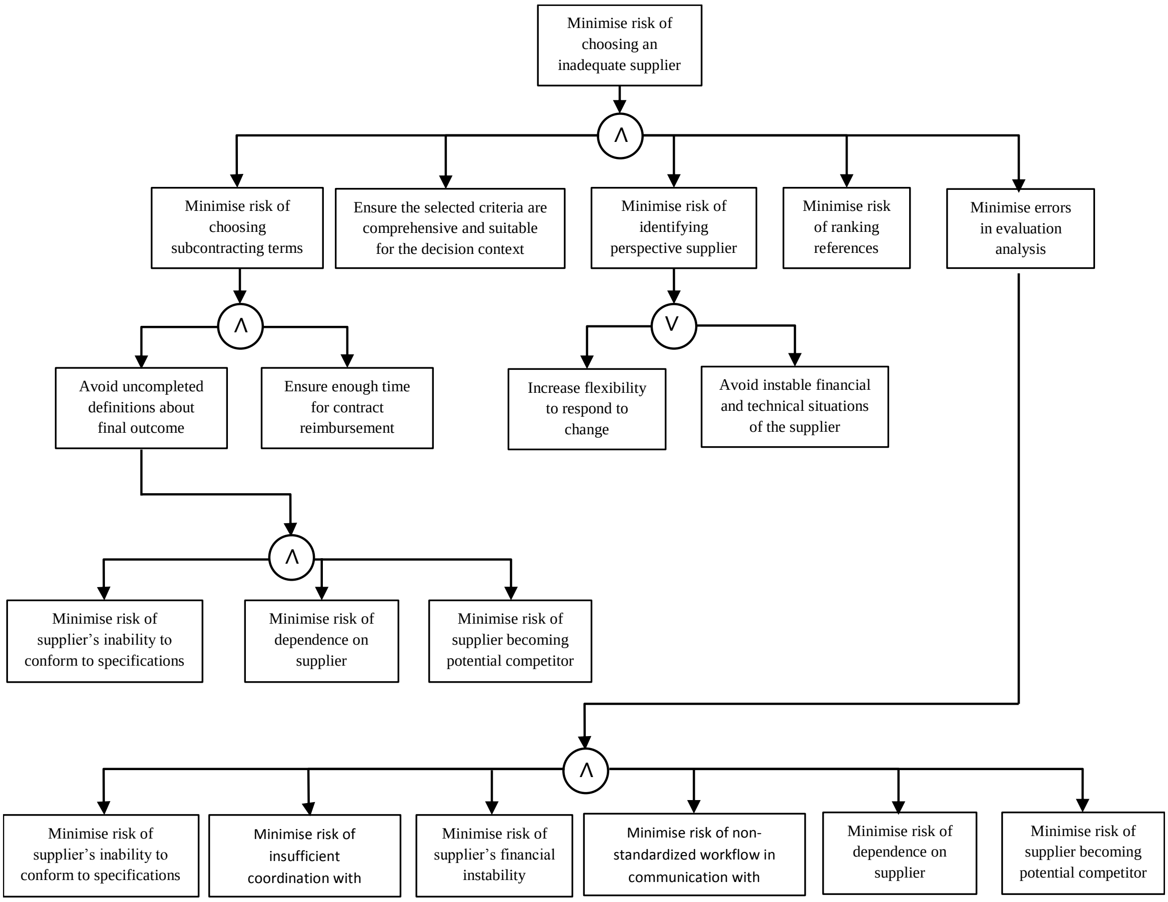


Figure 4-5. Final breakdown structure for risk evaluation for case study 1

4.1.3 Performance measurement phase

With the lack of detailed numerical information, the elementary risk measurement can be directly analysed with the qualitative evaluations that are provided by the expert team. The gravity of each elementary risk is directly expressed by linguistic descriptions (desired, acceptable, tolerable, intolerable and very intolerable) as shown in Table 4-3 for three suppliers (Suppliers 1, 2 and 3).

Table 4-3. Elementary risk expressions with linguistic descriptions for case study 1

	Inability of supplier to conform to specifications	Insufficient coordination with supplier	Supplier financial instability	Non-standardised workflow in communication with supplier	Dependence on supplier	Supplier becoming a potential competitor
Supplier 1	Tolerable	Tolerable	Intolerable	Intolerable	Tolerable	Tolerable
Supplier 2	Acceptable	Intolerable	Intolerable	Tolerable	Intolerable	Intolerable
Supplier 3	Intolerable	Acceptable	Very intolerable	Intolerable	Tolerable	Tolerable

With the defined triangle fuzzy numbers, these expressions are transformed into quantitative expressions. For the purpose of aggregation operation, these quantitative expressions are then normalised with the defuzzification function as shown in Equation 3-10. Table 4-4 presents the elementary risk expressions with triangle fuzzy numbers and the final normalised results for each candidate supplier. Higher numeric value indicates better risk evaluation result regarding one specific criterion.

Table 4-4. Quantitative elementary risk expressions for case study 1

	Inability of supplier to conform to specifications	Insufficient coordination with supplier	Supplier financial instability	Non-standardised workflow in communication with supplier	Dependence on supplier	Supplier becoming a potential competitor
Supplier 1	0.567 (.4,.6,.7)	0.567 (.4,.6,.7)	0.300 (.1,.3,.5)	0.300 (.1,.3,.5)	0.567 (.4,.6,.7)	0.567 (.4,.6,.7)
Supplier 2	0.677 (.5,.7,.8)	0.300 (.1,.3,.5)	0.300 (.1,.3,.5)	0.567 (.4,.6,.7)	0.300 (.1,.3,.5)	0.300 (.1,.3,.5)
Supplier 3	0.300 (.1,.3,.5)	0.677 (.5,.7,.8)	0.133 (0,.1,.3)	0.300 (.1,.3,.5)	0.567 (.4,.6,.7)	0.567 (.4,.6,.7)

4.1.4 Aggregation phase

4.1.4.1 Criteria weighting

As presented in Section 3.2.2, a judgement scale is applied to generate the weights which indicate the relative importance of each criterion in the specific decision problem. In the proposed methodology, the evaluation criteria are weighted through pair-wised comparison with a 1-9 linear scale, which originates from the AHP method. The results of criteria weighting defined by the evaluator in this case study are shown in Table 4-5

Table 4-5. Pair-wised criteria weighting for case study 1

	Inability of supplier to conform to specifications	Insufficient coordination with supplier	Supplier financial instability	Non-standardised workflow in communication with supplier	Dependence on supplier	Supplier becoming a potential competitor	Normalised weight
Inability of supplier to conform to specifications	1	4	2	6	3	7	0.37
Insufficient coordination with supplier	1/4	1	1/4	2	1/3	3	0.08
Supplier financial instability	1/2	4	1	5	3	6	0.28
Non-standardised workflow in communication with supplier	1/6	1/2	1/5	1	1/4	1/3	0.04
Dependence on supplier	1/3	3	1/3	4	1	5	0.17
Supplier becoming a potential competitor	1/7	1/3	1/6	3	1/5	1	0.06

This judgement should be verified by evaluating the consistency ratio (CR). In this study, CR is 0.06. It means that the judgments in the illustrated matrix are considered as not random. Then, the normalised weights are generated for each elementary risk expression (as shown in Table 4-5).

4.1.4.2 Aggregation operation

With the weighted average sum (WAS) approach, the overall performance can be calculated as shown in Table 4-6.

Table 4-6. Overall risk expression for each candidate supplier for case study 1

	Overall risk
Supplier 1	0.48
Supplier 2	0.45
Supplier 3	0.35

4.1.5 Graphical decision support

Because there is only one performance dimension involved in this case study, decision making can be developed based on the final evaluation risk instead of using graphical decision support approach. However, although trivial, the plot of the final risk evaluation results is presented to illustrate the visualised decision support phase in the proposed methodology. Figure 4-6 represents the overall risk expressions of all candidate suppliers in the case study.

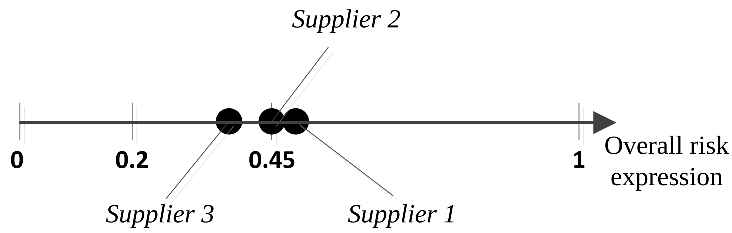


Figure 4-6. Overall risk for each supplier with the preference zones for case study 1

Regarding the risk analysis for the illustrated supplier selection process, different preference zones are defined by the evaluator for performance evaluation. They are: desirable risk within the range [0, 0.2], tolerable risk within the range [0.2, 0.45] and the unacceptable risk within the range [0.45, 1].

Two suppliers are in the zones of risk acceptability (Supplier 1 and Supplier 2). The third one (Supplier 3) falls in the unacceptable risk zone and must, therefore, be discarded. Then, it is up to the decision maker to decide between Supplier 1 and Supplier 2. A priori Supplier 1 is better positioned because it offers lower risk but other consideration such as price of parts can challenge this conclusion.

4.1.6 Discussion

This case study concerns a decision problem dealing with a comparison of different decision alternatives obtained from running a predefined process. This comparison is based on the overall performance evaluation carried out in the preliminary phase of a project. Although this case study focuses on only one dimension (risk), the same operations can be applied to cost and value assessment.

However, for some industrial projects, it may be difficult to identify a standard process with well identified main activities. Therefore, the breakdown analysis can only be developed on the basis of tools such as root cause analysis or objectives modelling. In addition, all the elementary performance expressions in this case study were based on linguistic expressions. However, they can be more diverse in general in terms of unit of measure and way of measurement.

For the purpose of further verification, a second case study still dealing with opportunity evaluation is presented for building construction projects to complete the application of the proposed methodology using all the evaluation axes.

4.2 Case study 2: Opportunity evaluation of construction projects

4.2.1 Background

Successful and highly efficient implementation of construction projects is the main purpose of every construction company. In most cases, a construction company simultaneously implements several projects which differ by complexity, duration, budget and variety of works. Therefore, it is important for the company to generate performance evaluation for each candidate project to improve the implementation with higher quality and profits.

Project performance evaluation during the implementation phase is a challenging problem due to the lack of up to date information (for instance, expenditures, profit, losses and accidents during the implementation phase of a candidate project) and criteria measurement know-how (selection of appropriate evaluation criteria and measurement methods). In this context, the data on the previously implemented projects should be collected and analysed as the references for new project performance measurement. In addition, qualitative evaluations (for example, survey or brainstorming) by a group of expert evaluators are also a source to obtain performance expressions.

In this case study, a construction company implements three different construction projects, namely P1, P2 and P3, at the same time. To make better use of shared material, financial and human resources to achieve higher profits, the company needs efficient performance evaluation for each of these projects during the implementation stage. This will make easier the company decision making for the allocation of enterprise resources based on the comparison of evaluation results.

The objective of this study is to apply and validate the proposed performance evaluation methodology in the context of comparing decision scenarios with limited, numeric and linguistic data for performance identification and measurement.

4.2.2 Identification phase

Because the decision problem concerns the comparison of performance for efficient allocation of enterprise resources to different projects, the construction company is considered to be the main stakeholder in this case. In addition, the performance evaluation period focuses on the implementation phase of these construction projects.

The benefits in this decision problem are summarised as: (1) increasing efficiency of the construction company in projects implementation and (2) internal and external improvement of the enterprise image.

Due to the lack of up to date information either on elementary performance variables or on the business process during the performance evaluation period, the reverse thinking with the question "*what are the elements that will cause the project failure?*" is applied to develop the top-down hierarchical structure for the purpose of performance measurement.

Further to this, it is considered that each basic element in the breakdown structure represents one performance variable. Therefore, the performance expression framework in this decision problem can be identified once the breakdown analysis is finalised.

4.2.2.1 Root cause analysis

In this case study, the cause and effect diagram (CED) is applied to develop the hierarchical objective structure. The final objective of the construction company is to achieve higher profit at the end of the implementation phase of the different construction projects. So, the project will be considered to have failed if it cannot generate enough profit for the company. The analysis begins with the top problem "project loss".

Then, the main factors that may cause this final problem are developed based on the result of a literature review. For a large construction project, Long et al. (2004) stated that the failure can be caused by five major factors: (1) incompetent designers or constructors, (2) poor estimation and change management, (3) social and technological issue, (4) site related issues and (5) improper techniques and tools. Zavadskas et al. (2014) concluded that some most commonly occurring nonconformities in construction projects are: (1) insufficient programme management, (2) insufficient control of project activities, (3) management of nonconformities, (4) nonconformities in project plan, (5) nonconformities of personal operations, (6) errors in documentation and mislead records, (7) insufficient management of critical processes, (8) nonconformities in environmental and work safety aspects and (9) nonconformities in work of suppliers and subcontractors.

Based on these assumptions, it is considered that the project loss can be caused by five major elements:

- Budget management issues which are related to the financial causes.
- Project profitability which is the percentage part of project earned profit in income generated by the project during implementation phase.
- Time management issues concerning the elements that will extend the duration of the project.
- Quality management issues which refer to the management of nonconformities in environmental and safety aspects, as well as in communication with suppliers.
- Project team management issues about human defects in the project implementation stage.

These elements are organised in a structure with further elements as shown in the cause and effect diagram (CED) of Figure 4-7.

The CED is considered as a common basis to develop the individual breakdown structure for the performance dimensions of cost, value and risk. If the relations among the elements in the CED and performance dimensions are identified, the CED can be transformed into top-down hierarchical structures of cost, value and risk. So, the following operation refers to the identification of evaluation criteria for development of breakdown structure and elementary performance measurement.

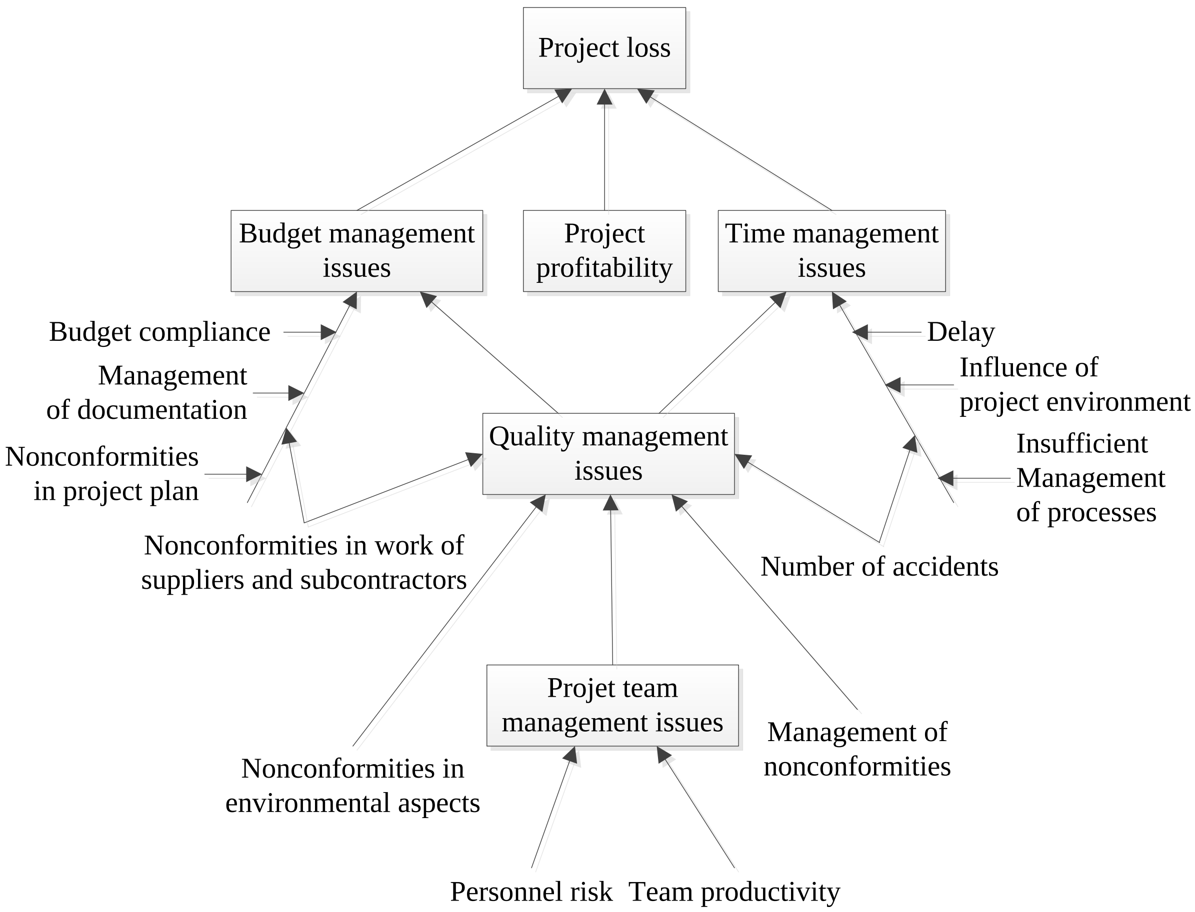


Figure 4-7. Cause-effect diagram of a construction project (adapted from (Zavadskas et al., 2014))

4.2.2.2 Identification of criteria

To generate the elementary performance expression for each basic component in the CED, Zavadskas et al. (2014) summarised a set of common evaluation criteria in construction projects according to the research results of authors in construction companies. Expert evaluation of factors affecting the overall performance is also taken into consideration in the selection. In this context, ten criteria are identified to generate the elementary performance expressions.

- Criterion 1 (C1): “project profitability” is described as the project profit rate in the project income that is generated during the implementation phase. It can be evaluated by experts according to previous experiences in similar projects.
- Criterion 2 (C2): “estimated project expenditures” is defined as the percentage of project expenditures with the income during the project implementation. If this ratio exceeds one, it means that the project should be terminated. Similarly as the first criterion, the expenditures and income can be estimated based on data of previously implemented projects.
- Criterion 3 (C3): “project team productivity” indicates the efficiency of project teams compared to one another. It is defined as a financial term which is expressed by the ratio between income generated during the implementation phase and the number of employees in the project team. A higher result represents better efficiency of the project team.

- Criterion 4 (C4): “number of accidents” refers to number of technical or security accidents during the implementation phase.
- Criterion 5 (C5): “nonconformities in project quality audits” represents the number of deviations from the specification or expectations of the project quality (for example, defects in planning or in cooperation with suppliers).
- Criterion 6 (C6): “delay of project close” describes additional time that is added to each project before closure.
- Criterion 7 (C7): “budget compliance” represents if the project expenditures are consistent with the predefined budget.
- Criterion 8 (C8): “documentation management” is defined as the evaluation on the errors in documentation and mislead records.
- Criterion 9 (C9): “environmental appraisal” is defined as the evaluation on environmental impact during the project implementation phase. Similarly as C8, both of them are qualitatively measured by linguistic expressions.
- Criterion 10 (C10): “personal risk” reflects the estimation of human defects in the project implementation phase.

Once performance elements and performance criteria are identified based on industrial practices, the relations among them and performance variables can be identified by evaluators according to previous experiences. Table 4-7 presents the all these selected evaluation criteria, their consistory with basic elements in CED and performance dimensions.

Table 4-7. Information on selected performance criteria for case study 2

Evaluation criteria	Elements in cause-effect diagram (CED)	Performance dimensions
Project profitability (C1)	Project profitability	Value
Estimated project expenditures (C2)	Budget management	Cost
Project team productivity (C3)	Team productivity	Value
Number of accidents (C4)	Number of accidents	Cost, Risk
Nonconformities in project quality audits (C5)	• Nonconformities in environmental aspects • Nonconformities in work of suppliers and subcontractors • Nonconformities in project plan	Risk
Delay of project closure (C6)	Delay	Cost, Risk
Budget compliance (C7)	Budget compliance	Value, Risk
Documentation management (C8)	Management of documentation	Value, Risk
Environmental appraisal (C9)	Impact on project environment	Value, Risk
Personal risk (C10)	Personal risk	Risk

4.2.2.3 Breakdown structure development

With the CED used as the reference hierarchical structure and the relations among evaluation criteria, basic elements in the CED and BCVR performance dimensions, the individual breakdown analysis of project cost, value and risk can be developed. Hence, the information from the CED reference base is transformed into individual hierarchical breakdown structures. Figure 4-8 shows the breakdown structure of the project cost.

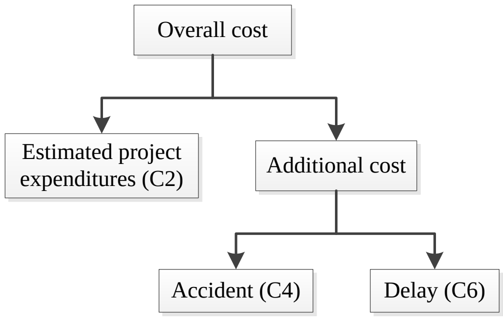


Figure 4-8. Breakdown structure of project cost for case study 2

Then, the breakdown structure of the project value is shown in Figure 4-9.

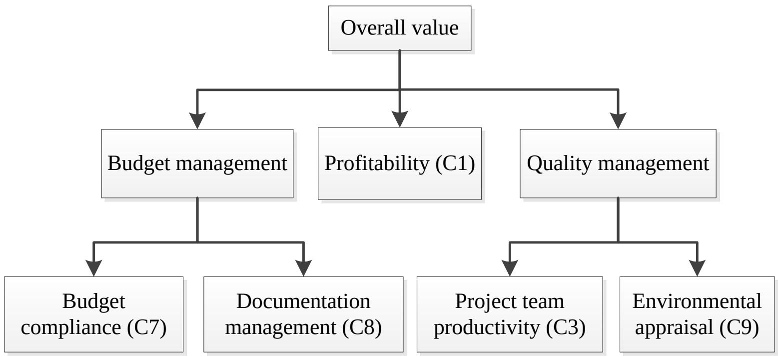


Figure 4-9. Breakdown structure of project value for case study 2

Finally, the breakdown structure of the project risk is shown in Figure 4-10.

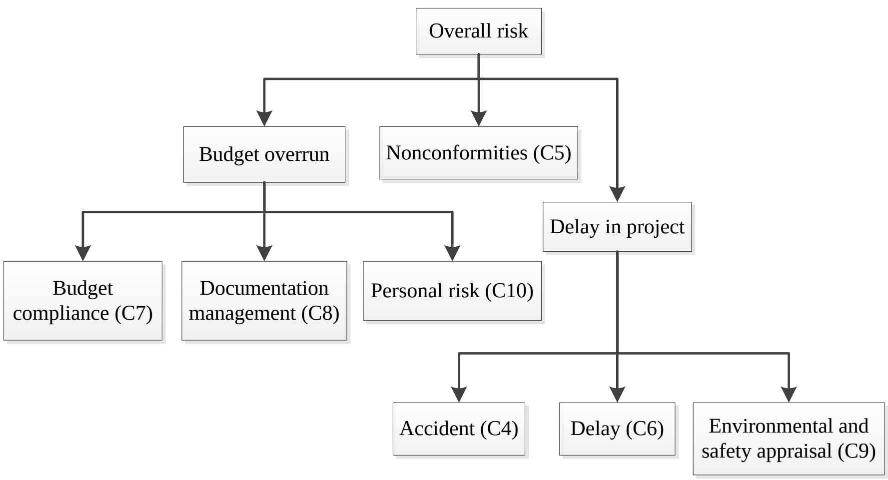


Figure 4-10. Breakdown structure of project risk for case study 2

4.2.3 Performance measurement phase

Based on the aggregated results of project audits which are described in the article of Zavadskas et al. (2014), the evaluation criteria are qualitatively or quantitatively measured as shown in Table 4-8.

Table 4-8. Elementary expressions of selected evaluation criteria for case study 2

Evaluation criteria	Units of measure	Project 1	Project 2	Project 3
Project profitability (C1)	%	4,00	7,20	8,72
Estimated project expenditures (C2)	$ (million euros)	0,960	0,928	0,913
Project team productivity (C3)	$ (million euros)/person	3,376	5,083	5,088
Number of accidents (C4)	Units	3	1	2
Nonconformities in project quality audits (C5)	Units	3	5	4
Delay of project closure (C6)	Month	6	7	3
Budget compliance (C7)	%	76	85	100
Documentation management (C8)	Linguistic expression	Acceptable	Acceptable	Desired
Environmental appraisal (C9)	Linguistic expression	Acceptable	Tolerable	Acceptable
Personal risk (C10)	%	45	80	30

For the purpose of aggregation, all these elementary measures should be normalised into a quantitative form (numeric numbers between [0, 1]). For numeric expressions, the evaluator defines the lower and upper limits for each criterion as shown in Table 4-9. Then, the elementary expressions are normalised by following the adjusted linear utility function as shown in Section 3.3.1.1.

Table 4-9. Lower and upper limits for quantitative criteria for case study 2

Evaluation criteria	Lower limits	Upper limits
Project profitability (C1)	0	12
Estimated project expenditures (C2)	1.28	0.85
Project team productivity (C3)	2.856	5.846
Number of accidents (C4)	5	0
Nonconformities in project quality audits (C5)	10	0
Delay of project closure (C6)	9	2
Budget compliance (C7)	60	100
Personal risk (C10)	90	20

For linguistic expressions, they are transformed into descriptions with triangle fuzzy numbers (desired (.7, .9, 1), acceptable (.3, .5, .7) and tolerable (.1, .3, .5)). Then, they are normalised by applying the defuzzification as shown in Equation 3-10.

Finally, the normalised numeric expression for each evaluation criterion is generated and presented as shown in Table 4-10.

Table 4-10. Normalised elementary performance expressions for case study 2

	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10
P1	0.33	0.74	0.17	0.40	0.70	0.43	0.40	0.50	0.50	0.64
P2	0.60	0.82	0.75	0.80	0.50	0.29	0.63	0.50	0.30	0.14
P3	0.73	0.85	0.75	0.60	0.60	0.86	1.00	0.87	0.50	0.86

4.2.4 Aggregation phase

4.2.4.1 Criteria weighting

In this case study, the elements of the cost breakdown structure are objectively measured. Therefore, it is considered that the weight for cost elements is always 1. Then, each basic element in the individual breakdown structures of value and risk should be weighted according to the evaluator preference. With the 1-9 linear scale, the evaluator gives the pair-wised judgments at each level of the individual breakdown structures. The consistency ratio (CR) and the weight are shown in Table 4-11.

Table 4-11. Consistency ratio and weights for value and risk elements for case study 2

<table>
<tr><th>Dimensions</th><th>Elements (level 1)</th><th>Weights</th><th>Elements (level 2)</th><th>Weights</th></tr>
<tr><td rowspan="3">Cost</td><td>Estimated expenditures (C2)</td><td>0.86</td><td>-</td><td>-</td></tr>
<tr><td rowspan="2">Additional costs</td><td rowspan="2">0.14</td><td>Accident (C4)</td><td>0.75</td></tr>
<tr><td>Delay (C6)</td><td>0.25</td></tr>
<tr><td rowspan="6">Value</td><td rowspan="2">Budget management</td><td rowspan="2">0.11</td><td>Budget compliance (C7)</td><td>0.80</td></tr>
<tr><td>Documentation management (C8)</td><td>0.20</td></tr>
<tr><td>Profitability (C1)</td><td>0.63</td><td>-</td><td>-</td></tr>
<tr><td rowspan="2">Quality management</td><td rowspan="2">0.26</td><td>Project team productivity (C3)</td><td>0.75</td></tr>
<tr><td>Environmental appraisal (C9)</td><td>0.25</td></tr>
<tr><td colspan="2">CR = 0.04</td><td colspan="2">-</td></tr>
<tr><td rowspan="9">Risk</td><td rowspan="3">Budget overrun</td><td rowspan="3">0.52</td><td>Budget compliance (C7)</td><td>0.56</td></tr>
<tr><td>Documentation management (C8)</td><td>0.12</td></tr>
<tr><td>Personal risk (C10)</td><td>0.32</td></tr>
<tr><td colspan="2">-</td><td colspan="2">CR = 0.02</td></tr>
<tr><td>Nonconformities (C5)</td><td>0.14</td><td>-</td><td>-</td></tr>
<tr><td rowspan="3">Delay in project</td><td rowspan="3">0.34</td><td>Accident (C4)</td><td>0.23</td></tr>
<tr><td>Delay (C6)</td><td>0.10</td></tr>
<tr><td>Environmental and safety appraisal (C9)</td><td>0.67</td></tr>
<tr><td colspan="2">CR = 0.05</td><td colspan="2">CR = 0.08</td></tr>
</table>

4.2.4.2 Aggregation operation

With the normalised elementary performance expressions and weights, the overall value and risk can be computed through selected aggregation operators. In addition, because the CED cannot provide any logical connector in the breakdown analysis, the relation among different elements with the same level in the structures is considered as an AND junction.

In this case study, both the weighted arithmetic sum (WAS) and the 2-additive Choquet integral are applied to generate the overall performance expressions. Table 4-12 shows the global performance expressions obtained for each alternative with the WAS method.

Table 4-12. Overall performance expressions with WAS for case study 2

	P1	P2	P3
Overall cost	0.70	0.80	0.82
Overall value	0.32	0.61	0.74
Overall risk	0.41	0,42	0,62

Table 4-13 shows the elements for aggregation computation with the 2-additive CI method. They are: (1) performance expressions for the performance variables at the second level (from the top) of each individual breakdown structure. To limit the complexity of the operation, they are still generated by WAS; (2) Shapley parameters v_i identified in the step of criteria weighting and (3) interaction parameters I_{ij} issued by the order of priority among different elements defined by the evaluator. Then, the overall performance expressions are presented in Table 4-14.

Table 4-13. Elements for aggregation with 2-additive CI for case study 2

	Cost variables		Value variables			Risk variables		
	Estimated expenditures	Additional costs	Budget management	Profitability	Quality management	Budget overrun	Nonconformities	Delay in project
Project 1	0.74	0.41	0.42	0.33	0.26	0.28	0.70	0.47
Project 2	0.82	0.67	0.60	0.60	0.63	0.41	0.50	0.41
Project 3	0.85	0.66	0.97	0.73	0.69	0.66	0.60	0.56
v_i	0.86	0.14	0.11	0.63	0.26	0.52	0.14	0.34
I_{ij}	I_{12}	-	I_{12}	I_{13}	I_{23}	I_{12}	I_{13}	I_{23}
	0.17		0.25	0.51	0.56	0.15	0.75	0.31

Table 4-14. Overall performance expressions with 2-additive CI for case study 2

	P1	P2	P3
Overall cost	0.67	0.79	0.81
Overall value	0.25	0.60	0.63
Overall risk	0.27	0,40	0,57

While comparing the aggregation results obtained with these two methods, it can be observed that the overall performance expressions are decreased using the second method. The reason is that without consideration of pair-wise interactions, the overall value and risk might be overestimated. The aggregation results with the 2-additive CI operator are supposed to be more accurate.

4.2.5 Graphical decision support

To help the evaluator in the comparison of different projects, the overall performance expressions that are generated by the 2-additive CI are displayed in the 3D (cost-value-risk) graphic. Figure 4-11 shows the graphical expressions for all candidate projects.

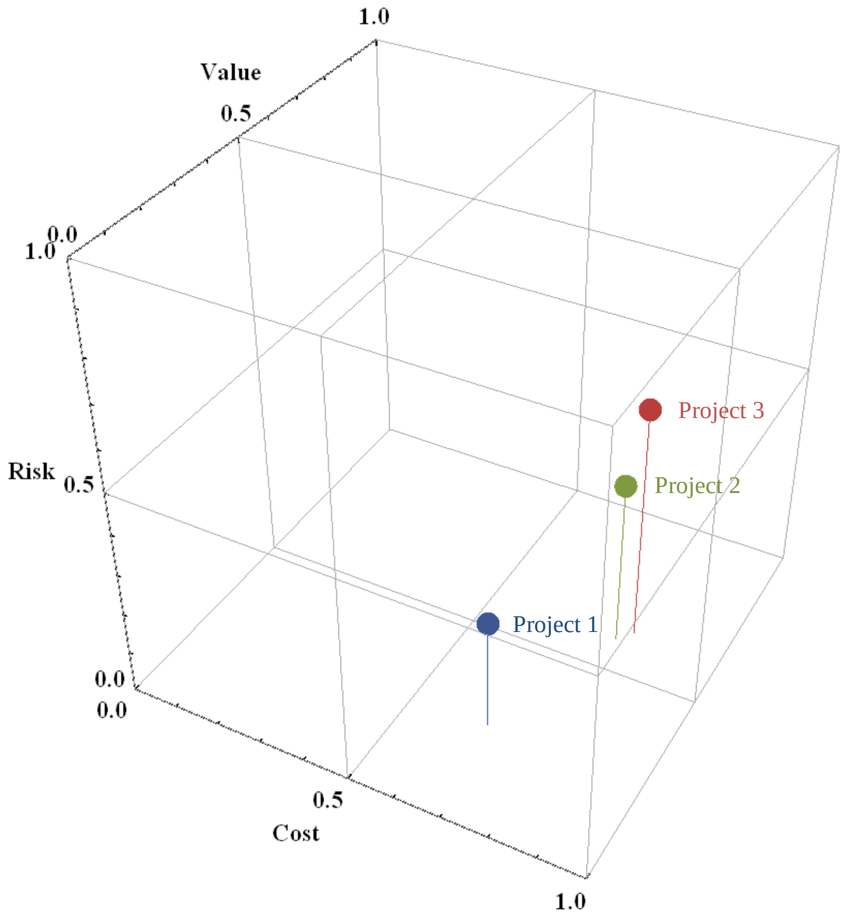


Figure 4-11. Plot of overall performance expressions for all candidate projects of case study 2

This graph shows that projects 2 and 3 have much higher value than project 1, while their cost and risk performance are also better. Between projects 2 and 3, project 3 can generate higher value with less risk and cost. Therefore, it can be considered that the order of priority among these three projects is: project 3 > project 2 > project 1.

4.2.6 Discussion

Because the elementary performance expressions mainly result from the data of the article of Zavadskas et al. (2014), the final decision making scenario is compared to the final research result presented in this article to test the proposed methodology. Considering consistency between the final results generated by the two methods, it is considered that the proposed methodology is reliable in this decision context.

This case study deals with a decision problem when comparing projects at a certain evaluation period (namely implementation stage) with limited up to date information for analysis. The biggest challenge in this context is the breakdown analysis to start the performance evaluation process. Based on previous experiences in similar projects and strategic modelling (for example, root cause analysis), the overall project performance can be broken down into individual hierarchical structures for each performance dimension with elementary performance expressions.

In conclusion to the first two case studies, they have illustrated that the proposed methodology can be applied to decision making problems concerning comparison of several alternatives with well-defined project activities or without up to date information. To verify this methodology in a more global situation such as project monitoring, the third case study applies the methodology to evaluate project performance at each stage of a given project to adjust the action plan and control success of the project.

4.3 Case study 3: IT development project monitoring and control

4.3.1 Background

This case study comes from a real IT project carried out in a European institution. The goal was to replace an existing but obsolete application by a new one, redeveloped from scratch with state-of-the-art technology and to be integrated in the document management ecosystem of the institution.

The existing IT application, named Adonis, was used daily by the organisation (mostly by secretaries of the various departments but in fact open to everyone) to register official mails (received or sent) by the institution with the attached documents. This mostly concerns paper mail (e.g. the mail of the President, the mail of VIPs (very important people)), but also invoices, contracts, legal notices and mail exchanges with other European or State Institutions. The paper documents are scanned, given an identification code, classified by means of meta-data and registered in electronic form with indication of issuer, distribution list and list of authorised readers.

Adonis was a stand-alone IT application developed as a client/server architecture application in PowerBuilder technology with a dedicated Oracle database. It was managed locally by an administrator and his assistant. Especially, the administration team had to manually maintain the list of users (internal to the institution) and the list of external contacts (legal entities or persons). In addition, the application came to out of support in 2012 and had to be replaced by a new application (named Adonis2).

Therefore, the organisation decided to replace the current Adonis application by a new one based on Microsoft SharePoint 2010 technology and its Document Centre (for document management) with the same set of core functionalities than the existing application, for example:

- Registration and classification of internal and external document exchanges sent or received by mail or e-mails, called “entries”;
- Attachment of documents to the entries, if applicable;
- Notification to users or groups of users, reminder and acknowledgement;
- Links between related entries;
- Management of access rights according to user roles;
- Statistics.

The new Adonis application should also be integrated to the other documents and records centred applications (for example, the records management system and the Intranet) of the organisation.

Rebuilding the application was also an opportunity to rationalise the functional architecture of the application while reducing the workload of the application administrator team by externalising a set of functionalities (automatic maintenance of the users list by using the enterprise user directory – or LDAP and automatic maintenance of the contact list using another application that already does it).

In this context, the main objectives of this IT development project were:

- The replacement of the existing PowerBuilder application by a new SharePoint-based version with the same core functionalities;
- The replacement of redundant functionalities in the current application by using standard IT solutions of the organisation; for example, reuse taxonomy of keywords (document types and categories) and list of external organisations managed by another new external reference repository also used by the Intranet;
- The migration of the legacy data, e.g. all existing entries and documents, form the current application to the new one.

A preliminary study was carried out prior to the IT development project to analyse the functional requirements, define the proposed functional solutions and study the complementarities with the other document centred information systems of the institution. In this study, the proposed solution was documented in a report including the following tasks:

- Building the new application on the basis of a set of detailed specifications of the core functionalities (listed in the report), the externalised functionalities and the internal architecture of the new application;
- Building the migration module on the basis of provided specification of the migration policy and the development of the migration tool (detailed in the report);
- Implementation of the new application through migration operations, IT tests and integration test with other applications.

The case study only concerns the analysis and IT development phases of Adonis2. The objective of the case study is to monitor and control the execution of the Adonis2 development project by applying the proposed performance management methodology to ensure the consistency between the predefined objectives and the final outcome of this project. The case study shows the application of the proposed methodology to performance evaluation in one specific phase of an IT project and also to project monitoring based on several evaluations along the project life history.

4.3.2 Project history

The project started in November 2011 and was supposed to deliver in January 2014. It started with a 4-month preliminary study to establish the user and functional requirements and to define the functional and physical architectures. This analysis was delivered on-time in April 2012 (with a budget of 21 404.80 €). This was followed by an internal analysis for the elaboration of the project charter and its official approval (from April until the end of September 2012 – no contractual cost because done internally). Approval was obtained on 01/10/2012 and the IT development could start.

The first development phase started on 03/12/2012 to be completed by 31/07/2013. Two developers (a principal specialist and an analyst/programmer) were hired at a cost of 102 169.20€ (including 22 000€ for the elaboration of technical specifications) to design, build, test and deliver the first set of functionalities of Adonis2 (user interface, business modules, data management, interface with the corporate user repository and access rights management, interface with SharePoint Document Centre, interface with scanner facility to digitalise paper documents and data migration tool). In June 2013, a decision had to be made to fire the developers and replace them by a new team because the application was not delivered and the .Net framework created was lacking the functional components. The first investment was nearly lost and the project was in big trouble.

A new development iteration, with an additional budget, started on July 2013 to last until 28/12/2013 with two developers at a cost of 92 211.84 € to deliver Adonis2 V1 with the same goals as the previous task but without the migration tool. The application was delivered in production but not opened to users because key users requested additional developments.

A new contract was signed to cover the period 01/10/2013 until 31/03/2014 to interface Adonis2 to SharePoint TermStore (for metadata management) and to DCS Web Service for document management in the SharePoint Document Store. This led to Adonis2 V1_2 at an additional cost of 76 843.20 €. A budget extension of 17 546.16 € was needed to complete minor evolutions again requested by the key users. Key users, end users and system administrators were trained in November-December 2014 and key users requested again evolutions before the application can go live. This implied an additional cost of 32 932.80 € for the period 26/02/2014 until 13/06/2014 as well as user frustration for the delay of putting the application in production (the project is 6 months late).

A budget extension of 5 488.80 € was needed from 19/05/2014 until 30/06/2014 to cover minor evolutions. The first user acceptance test campaign could be made and the application released in production in September 2014. At this time, the system performance was acceptable (number of incidents < 1/month, response time < 5s and user satisfaction good).

Then, by the end of 2014, the Adonis2 performances seriously deteriorated (number of incidents > 30/month, response time > 15s, user satisfaction very bad and data accessibility problems). This created a crisis situation in the institution (with official complaints from the President himself and end users refusing to use the system). The problems were due to internal bugs in the use of Microsoft APIs (application interface programmes) between SharePoint and its Document Centre. The decision to remove the Document Centre and replace it by a dedicated database had to be made.

This decision led to the creation of a new contract of 22 950 € to cover the period 21/05/2015 until 31/08/2015 for the implementation of the new solution (revise the physical architecture and replace SP Document Centre by a dedicated SQL Server database and a file share solution). A new user acceptance test campaign could be made and Adonis2 V1_5 could be released in production. This seriously improved the situation (number of incidents < 1/month, response time < 5s, user satisfaction good and data accessibility good) by the end of August 2015.

As it can be seen from this story telling, the execution of the project faced serious management problems creating internal tensions between the system owner (Directorate of the Presidency) and the system provider (Directorate of IT), stress of the IT project manager, pressure on IT developers and high user disappointment. This had a negative impact on the image of the Directorate of IT. It was therefore necessary to regularly assess cost expenditure, risk evolution and business value of the project to decide whether the project can continue or should be stopped.

4.3.3 RUP IT methodology

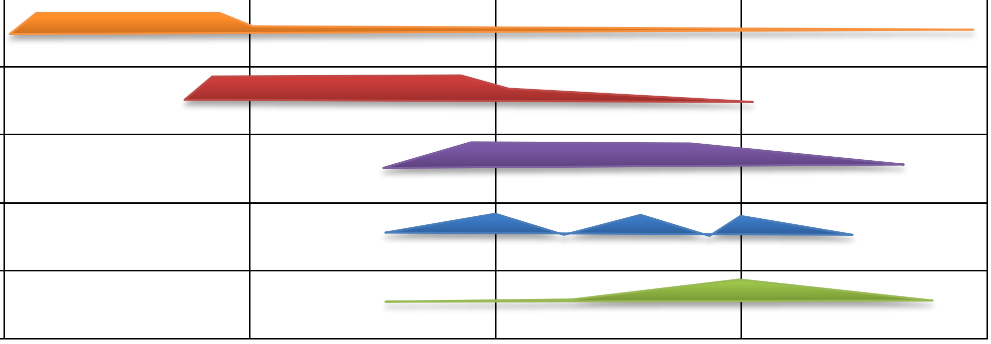
A well-established and widely used methodology for IT development is the Rational Unified Process (RUP) framework, originally devised by Jacobson et al (1999). RUP has therefore been selected for the case study as a suitable tool to manage the different life cycle phases of the IT development project.

RUP is organised along horizontal and vertical dimensions. The horizontal one describes the dynamic structure of a project with four life cycle phases: inception, elaboration, construction and transition. The vertical one represents the static structure in terms of disciplines, activities and workflows along the life history of the project (Cooper et al., 2006).

A practical visual way to present the horizontal and vertical dimensions of RUP is the RUP hump chart reproduced in Table 4-15.

Table 4-15. RUP hump chart of IT development projects

	Inception	Elaboration	Construction	Transition
User requirements				
Analysis & Design				
Implementation				
Test				
Deployment				



4.3.3.1 Inception phase

In this phase, the user requirements are identified through communications with the users (especially the key users) of the application to be developed or on the basis of a business analysis (analysis of system functions, data and information flows, workflows, etc.). Based on the comprehension of the user requirements, it is decided whether to use existing business tools or commercial software packages (possibly in collaboration with external business partners) or to develop a new IT application (i.e. specify, program, test and release the new application).

The main deliverable of this phase, in addition to the requirements definition book, is the vision document (or project charter) that provides objectives of the project, an estimation of the overall cost of the project, a rough planning, an analysis of alternatives, a project management structure and a first evaluation of project risks.

4.3.3.2 Elaboration phase

Based on the definition of user and system requirements, the detailed specifications, the technical architecture and the legacy migration specification of the new application are defined in this phase.

The main deliverables of this phase are: detailed technical specifications, data architecture, physical architecture, the software development plan (which is a detailed project plan) and a risk list.

4.3.3.3 Construction phase

This phase corresponds to the actual coding of the application with relevant unitary tests at different steps of the software development. These tests are used by the project team to verify that all the elements in the application properly work. In RUP, the development can be organised in several successive iterations to develop the software application in a modular and progressive way (which was the case in the Adonis2 case study).

In addition, other kinds of test should be carried out to comprehensively check the application. Firstly, the unit tests separately validate the proper functioning of each function (such as, for instances, registration and classification of document exchanges, attachment of documents, notification to users, management of access rights and statistics in Adonis2). Then, the integration tests validate two things: the functioning of the whole application while assembling all modules together and the compatibility between this new application and other applications of the organisation (for examples, records management system and Intranet of the institution for Adonis2).

The main deliverables of this phase are: the software product ready for release in production, the test plan (documenting all test scenarios) and the software documentation.

4.3.3.4 Transition phase

The last phase concerns the release of the application in its production environment. It first includes the user acceptance tests (UATs) to be run to validate if the new application meets all needs expressed by the users. Based on results of the UATs, end users may request evolutions and bugs detected must be corrected. This may result in a new campaign of UATs to be included in this phase. Legacy data migration from the old system to the new one is also part of this phase, if it applies. In addition, if necessary the phase also includes end user trainings performed by key users (internal to the company) or by professional trainers (external to the company). It can also include promotion or publicity of the application to its future audience.

The main deliverables of this phase are: user acceptance test results, the final version of the application, user guide of the application, administration guide and training support (if training is needed).

4.3.4 Identification phase

As the initial step of the proposed methodological framework, the aim of the identification phase is to analyse the context regarding the particular decision problem. In the context of this particular case study, the aim is to identify project benefits, all relevant stakeholders, evaluation periods and performance variables for the Adonis2 development project.

4.3.4.1 Benefits

With the realisation of this IT development project, some expected benefits of Adonis2 identified in the preliminary study can be listed as follows:

- Alleviating the maintenance risk created by the phase-out of the PowerBuilder application
- Improving the user experience and user productivity thanks to the new user interface integrated on one screen
- Reducing the workload of end users by suppressing multiple declarations of the same set of document metadata
- Enhancing the reliability and searchability (by means of multi-criteria search) of the document management system

- Simplifying the work of the application administrators of the current application by removing manual and redundant declaration of common information (e.g. creating or renaming organisation units, creating new users, updating user allocation to units…)

It is considered that most of these potential advantages are intangible during the project life history. They can only be qualitatively analysed and assessed at the end of the project. Therefore, these expected benefits do not belong to any specific phase of the project.

4.3.4.2 Stakeholders

In most IT development projects, the main stakeholders are: the system owner or the sponsor who validates and approves the project (because s/he usually is responsible for the business area or the related business processes), the project team (project manager and team members), the system provider who must deliver the software or IT product (for example, the IT project manager and the IT department), the external business partners (in the case of externalisation or alternative solutions) and the business users.

For the purpose of monitoring and control, the system owner (in this case, a director representing the institution) is considered as the most important stakeholder in the Adonis2 case study. The analysis will be developed from his point of view. However, the business users (or end-users) of the new application should not be neglected in practice, because they directly determine the real business value of the project. In this project, the business users are divided in two categories: the key users and the end users. The former group is made of users who extensively use the system and act as referents to train other potential users of the system, the latter group is made of all the employees of the organisation who will potentially use the application.

4.3.4.3 Evaluation periods

Unlike *a priori* decision problems that focus on one performance evaluation period, more than one phase are involved in the case of project monitoring and control. Indeed, the goal is to evaluate the situation at certain points in time (or milestones) of the project and to make decisions depending whether the project is on-time and on-budget or not or even at risk.

In the IT development project, evaluation periods were necessary at some project milestones to sustain management decisions. The first milestone was the project charter issued from the preliminary study. The other three milestones are the releases of different versions of Adonis2, especially to assess the value of Adonis2 for the end users and the institution.

4.3.4.1 Evaluation variables

Performance evaluation variables are defined to be the basis for measuring the progress of the project along its life history. Regarding the particular context of this IT development project, the system owner mainly focuses on the overall cost of the development of the new application, the respect of the due date and the satisfaction of the users. Meanwhile, the end users focus on a satisfactory (i.e. efficient and effective) user experience (more specifically, fast response time, efficient functionality, reduced effort and efficient look and feel).

Relevant evaluation elements involved in the variables of cost, value and risk in the different life cycle phases of the project are presented in Table 4-16.

Table 4-16: Performance evaluation elements in each life cycle phase of the information project for case study 3

Dimensions	Variables	Descriptions	Inception	Elaboration	Construction	Transition
Cost	Preliminary study	All necessary spendings on the analysis of the general architecture of the application	√			
	Development	All necessary spendings related to design and coding of the new application		√	√	
	Data Migration	All necessary spendings on data transformation				√
	Testing	All necessary spendings on software test			√	√
Value	User experience	Ease of use of the new application and satisfaction of the user interface				√
	Productivity	Increased productivity for all users (time saving)				√
	Utility	Contacts and documents can be shared with other applications of the organisation				√
	Quality	Reliability of the service regarding the encountered problems or errors				√
Risk	Poor system acceptance	End users dissatisfaction/complaints			√	√
	Planning defects	The planning is not efficiently made and controlled	√	√	√	√
	Budget overrun	Budget exceeded compared to estimation	√	√	√	√
	Resource unavailability	The necessary resources (methods, tools and equipment…) are not correctly defined or are unavailable	√	√	√	√

4.3.4.1 Breakdown structure development

Once the performance variables are identified, the breakdown structure can be established through objectives modelling using the VFT method. The hierarchical structure consists of strategic, fundamental and means objectives from the highest to the lowest levels.

The initial fundamental objective (FO) of this IT development project was “replace the current Adonis application with a new version guaranteeing end user satisfaction by January 2014”. It can be further explained by several means objectives (MO) that can be considered as its essential components regarding the basic functions of the new application. They can be summarised as:

- MO 1: Rewrite the application code and provide a new user interface
- MO 2: Interface the user repository of the new application with the institution user repository (in this case, Active Directory)
- MO 3: Integrate the Adonis documents to the corporate document manager (in this case, SharePoint Document Centre)
- MO 4: Manage user access rights to Adonis data from Active Directory information
- MO 5: Migrate the legacy data of Adonis (entries, documents and related metadata) from its Oracle database to the SharePoint Document Centre
- MO 6: Improve user productivity (i.e. reduce average elapsed time to encode a record to about 15 minutes)

This objective breakdown structure will be applied as a basis for individual breakdown analysis of each performance dimension.

The cost structure of an IT development project is well established in the literature and well known by IT project managers. It has little variation in different contexts. In addition, the number of cost variables in this project is limited. So, the dimension of cost can be directly quantified without going through the breakdown analysis. The cost variables can be directly allocated to the different life cycle phases. These are:

- The analysis costs of the preliminary study (mostly consulting fees of an external service supplier company) realised as a time & means contract (i.e. ordered number of days at a predefined rate)
- The development costs (including technical specifications, coding, unit and integration testing and software documentation writing) made of a series of time & means contracts and fixed-price contracts
- The data migration costs (including the development of the data translation system, the transfer of the data and the validation tests)
- The testing costs (covering test plan elaboration, support to run user acceptance tests and writing test reports) made of a series of time & means contracts to employ a test expert

There is no infrastructure and data centre costs in this case because the organisation has its own data centre and it used existing servers, software licences and data storage.

The value for both the system owner and the end users of this IT system will mainly be a function of the end user satisfaction of the released application. Therefore, the evaluation period for the dimension of value concerns the last two life cycle phases, i.e. when the application will be open to end users. In addition, only one hierarchical value structure is needed to be developed because the structure of the value equation will remain the same for any case.

To generate the value structure, the identified means objectives should be associated with the four identified value variables. Table 4-17 presents the relations between these elements.

Table 4-17. Relation between value variables and means objectives for case study 3

Value variables	MO1	MO2	MO3	MO4	MO5	MO6
User experience	√	-	-	-	-	√
Productivity	-	-	-	-	-	√
Utility	-	√	√	-	√	-
Quality	-	-	-	-	-	√

If one means objective is associated with one value variable, it means that the accomplishment of this objective will generate one elementary value. However, some means objectives do not have related value variables. This indicates that elementary value generation is not directly impacted by accomplishment of these objectives. In addition, some variables are associated with more than one means objective. The same variable appeared only one time in the breakdown structure in order to avoid repeated computations in aggregation operations. For example, although the value variable "utility" is linked to means objectives MO2, MO3 and MO6, it appears only one time at the lower level of the overall value instead of three times in the value breakdown structure.

Based on this association, the breakdown structure for the dimension of value can be developed as shown in Figure 4-12.

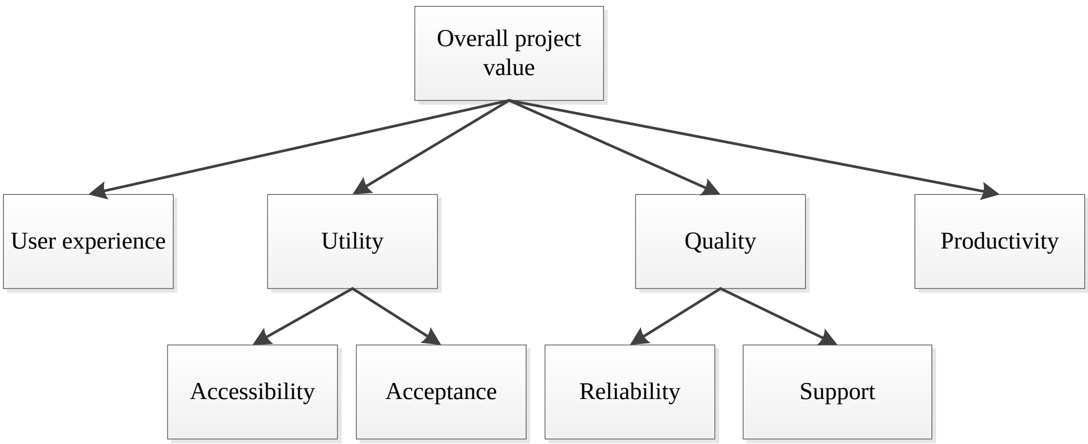


Figure 4-12. Value breakdown structure for case study 3

Some variables are further broken down for the purpose of measurement. The utility is divided into two elements: (1) data accessibility between the new application and other existing IT tools in the organisation and (2) acceptance of Adonis2 by the end users. The quality is reflected through the reliability of the application and related support service.

The anticipated risks for the project owner can be summarised in four aspects: (1) delays in programming which will imply delay of the project due date, (2) unexpected costs which will result in overspending, (3) poor end user acceptance and (4) unavailability of necessary nonfinancial resources.

They are reflected by the risk variables identified in Table 4-16. Similar to the analysis for the dimension of value, the risk evaluation was developed based on the relations between the means objectives and risk variables, as shown in Table 4-18.

Table 4-18. Relation between risk variables and means objectives for case study 3

Risk variables	MO1	MO2	MO3	MO4	MO5	MO6
Poor end user acceptance	√	-	-	-	-	√
Planning defects	√	√	√	√	√	√
Budget overrun	√	√	√	√	√	√
Resource unavailability	√	√	√	√	√	√

Because almost all risk variables are involved in each means objective, it is considered that the same risk structure can be applied to all life cycle phases of this IT project. Based on this association, the risk structure of this IT development project is developed as shown in Figure 4-13.

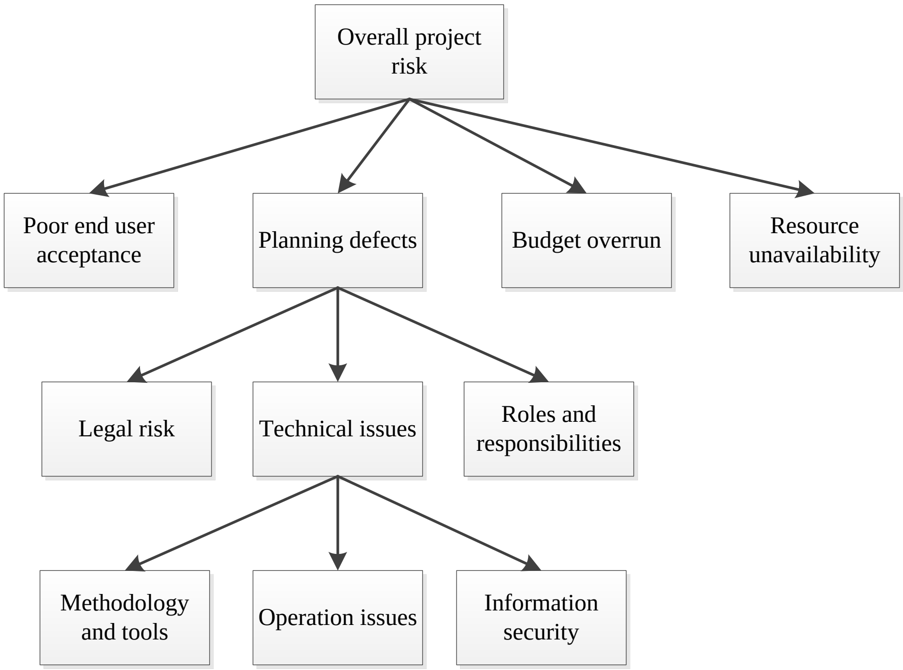


Figure 4-13. Risk breakdown structure for case study 3

In the current case study, the on-time delivery of the Adonis2 application is the most critical objective for the system owner. So, further analysis is required for the risk variable “Planning defects”. By following the proposed risk classification (as described in Appendix B), lower level risk variables are identified such as legal risk, technical issues and roles and responsibilities (for human defects).

Since the focus is more on the technical aspects, the variable “Technical issues” is further detailed into defects related to the involved methodology and tools used for the software development (RUP), operation issues and information security problems.

Once the individual breakdown structures are identified for the relevant performance dimensions, the elementary performance expressions within each axis are directly identified (for the dimension of cost) or measured with selected evaluation criteria (for the dimensions of value and risk). The following section presents the detailed information on the performance measurement phase.

4.3.5 Performance measurement phase

4.3.5.1 Cost measurement

All the project cost variables are quantitatively expressed in monetary terms. They are recapped as shown in Table 4-19.

Table 4-19. Elementary cost expressions for case study 3

Cost variables	Elementary expressions (€)
Preliminary study cost	21 405
Detailed specifications	22 000
Development cost 1	80 169
Development cost 2	92 212
Development cost 3	99 896
Development cost 4	32 933
Data migration cost	22 950
Testing cost 1	7 020
Testing cost 2	1 600
Testing cost 3	1 060

Some cost variables are divided in different parts because they appear in different RUP iterations. For example, the development cost is divided into four parts: (1) cost referring to the creation of the .Net Framework without delivery of functional components, (2) cost concerning the completion of functional component development, (3) development cost of user interface due to additional user group requests and (4) cost regarding evolution required by the business user group due to issues with SharePoint performance. Similarly, the testing cost is also split into three parts that correspond to three UAT testing phases for Adonis2 during the whole period of this project.

As the cost variables are cumulative, these elementary expressions can be directly applied to generate the overall cost for a given evaluation period. The overall cost in each period can be computed as the cumulative sum of all involved elementary cost expressions of costs consumed so far.

Table 4-20 presents the project cost expressions by each evaluation period and their associated sum.

According to the project charter, the initial budget allocated was 180 000 euros. Table 4-20 shows that the project expenditure was high in the first two development stages (due to the loss in the 1st development iteration). That made the project into over-expenditure in the second period. Thus, the project owner had to decide whether the project should be terminated or could continue. In this case study, an additional funding of about 200 000 euros was added in order to complete the project.

For comprehensive performance expression for decision support on the dimension of cost, the quantitative cost expressions should be normalised into real numbers between [0, 1] by using Equation

3-8 or Equation 3-9 depending whether the initial budget can be modified or not (as explained in Chapter III, Section 3.3.1.1).

Table 4-20. Project cost expressions for case study 3

Evaluation periods	Project milestones	Involved cost variables	C_k (€)	Cumulated cost (€)
Period 1	Project charter	Preliminary study cost	21 405	21 405
Period 2	Version 1 of Adonis2	• System specification • Development cost 1 • Development cost 2 • Testing cost 1	201 401	222 805
Period 3	Version 1_2 of Adonis2	-	-	222 805
Period 4	Final version of Adonis2	• Development cost 3 • Development cost 4 • Testing cost 2 • Data Migration cost • Testing cost 3	158 439	381 244

In this case study, the system owner accepted to modify the project budget to cover the over-expenditure. Therefore, the costs of each evaluation period are normalised based on an acceptable zone initially ranging within [0, 180 000] euros and then within [180 000, 380 000] euros for the revised budget. It means that the best result is when the project is finished with planned expenditure or less than the initial budget (initially 180 000 euros). However, because the project budget was modified after the second evaluation, the period had to be renormalised and the maximum acceptable expense should normally not be more than the modified budget.

Figure 4-14 presents the final normalised results of the project cost for each evaluation period using Equation 3-10 and its evolution along the life history of the IT development project. On this [0, 1] scale, the higher value indicates that the project has better performance in terms of cost.

In this case, the spending accumulates along the project life history, while the cost performance expression decreases with time (due to the loss in the initial phases and costs of extra requests). It can be seen that the final expenditure of this IT development project was almost two times higher than the budget initially announced in the project charter. The cost performance decreased rapidly during the second evaluation period due to serious changes required by key users and to remedy end user dissatisfaction. Although the system owner accepted to modify the project budget to cover the over-expenditure, the final cumulated expense (as described in Table 4-20) still exceeded the maximum acceptable expense (380 000 euros). So, the cost performance expression of the last evaluation period decreased to 0 according to Equation 3-9. In a normal case, it should have stayed above the 0.50 line.

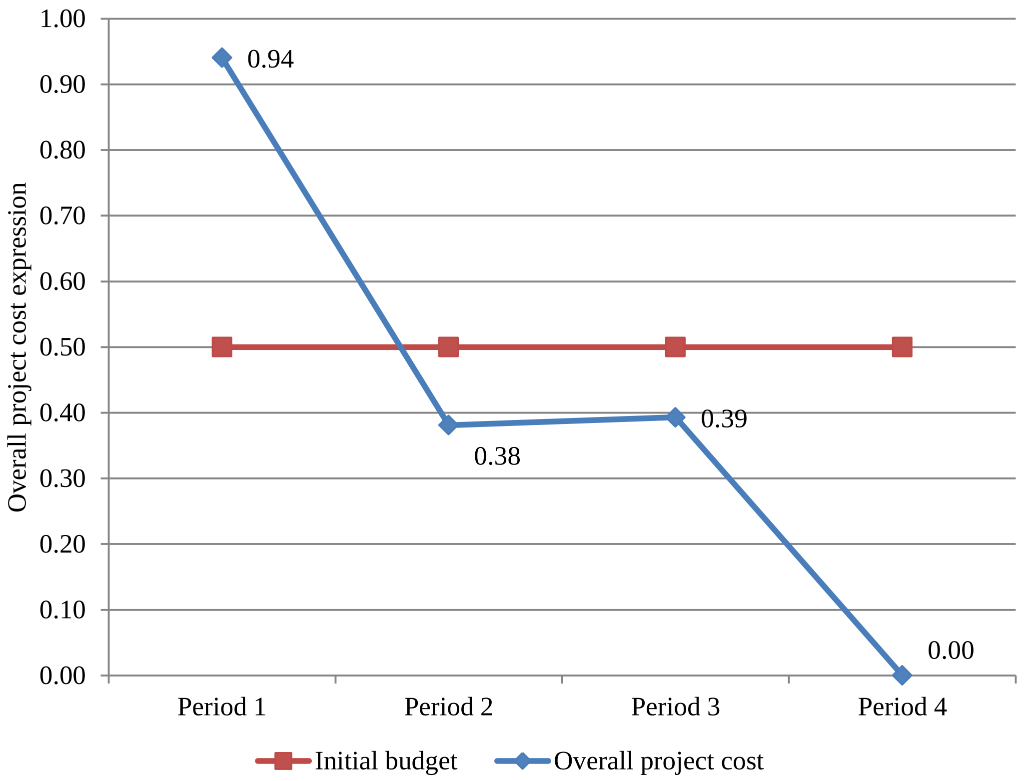


Figure 4-14. Overall project cost expressions for case study 3

4.3.5.2 Value measurement

For elements at the basic level of the value structure, evaluation criteria are selected to directly generate the elementary expressions. The user experience is evaluated by means of a user survey which contains questions on the ergonomics, user-friendliness, response time and defect rate of the system as well as reactivity of the IT support service. These terms are thoroughly evaluated by end users with numeric ratings (on a [1, 10] scale). Then, these feedbacks will be integrated in a final evaluation result to reflect the user satisfaction on the new application. The productivity is mainly evaluated in terms of the response time of the application. The utility is measured through the data accessibility and percentage of users using the application. The quality can be further analysed through the number of incidents by month and the mean time for solving incidents.

The elementary values were assessed three times in this case study (value was not assessed in the first evaluation period because there were no relevant data available at this stage). The first measurement of value was done after the first release of Adonis2 in production. The second measurement was performed during the crisis stage to assess the situation and make a decision. The last measurement was performed after migration and correction of technical errors to verify impact of corrections made. Table 4-21 presents the evaluation criteria and measurement results obtained from surveys and tests.

Table 4-21. Value evaluation criteria and measurement results for case study 3

Value variables	Evaluation criteria	Units	Period 1	Period 2	Period 3	Period 4
User experience	User satisfaction	-	-	Good	Very bad	Good
Productivity	Response time	Second	-	5	15	5
Accessibility	Data accessibility	-	-	Fair	Fair	Good
Acceptance	Percentage of users	%	-	85	10	60
Reliability	Incidents rate	Number/month	-	1	30	1
Support	Mean time for solving incidents	Hour	-	4	8	4

The result of value measurement contains quantitative and qualitative expressions. Both user experience and accessibility are expressed by linguistic expressions and the other criteria are quantitatively measured. These elementary value expressions are normalised into real numbers between [0, 1] for further aggregation operation. For the quantitative expressions, the evaluator should define the expected best result and the acceptable worst result to identify the acceptable zone for each evaluation criterion. Then, the elementary expressions are normalised using Equation 3-6. The results are shown in Table 4-22.

Table 4-22. Normalised value expressions for quantitative criteria for case study 3

Evaluation criteria	Acceptable zones		Normalised value expressions		
	Worst results	Best results	Period 1	Period 2	Period 3
Incidents rate	10	0	0.90	0	0.90
Mean time for solving incidents	16	2	0.86	0.57	0.86
Response time	8	3	0.60	0	0.60
Percentage of users	95%	100%	0	0	0

For the qualitative expressions, the linguistic variables should be transformed into fuzzy numbers. Then, they are expressed as one single numeric number using Equation 3-11. Table 4-23 shows the results of the normalisation.

Table 4-23. Normalised value expressions for qualitative criteria for case study 3

Evaluation criteria	Expressions by fuzzy numbers		Normalised value expressions		
	Construction	Transition	Period 1	Period 2	Period 3
User satisfaction	(0, 0, .1)	(.3, .5, .7)	0.50	0.03	0.50
Data accessibility	(.1, .3, .5)	(.3, .5, .7)	0.30	0.30	0.50

Remark: It can be noted that the same measurement can then be done again every 6 months once the system is regularly running in production to check that user experience and productivity remain satisfactory and that acceptance and reliability increase; if not, correction actions must be taken.

4.3.5.3 Risk measurement

The risk analysis in this case study is developed through quantitative evaluation through numeric rating. For each elementary risk, which does not have lower level elements in the breakdown structure, the evaluator gave a score (from 0 to 4) on its likelihood and possible impact. Lower score means higher likelihood and more serious impact of one specific risk, while 4 indicates very high risk and 0 represents no risk. Then, a criticality index (C) is computed using Equation 4-1.

$$C = L \times I \tag{4-1}$$

Where, L and I are the scores on the likelihood and possible impact of one elementary risk.

Most of the identified elementary risks are involved in different evaluation periods, their likelihood and impact vary over time. Therefore, the risk measurement was generated in each period for the purpose of project monitoring. Table 4-24 shows the results of risk measurement.

Table 4-24. Risk measurement results for case study 3

Phases / Variables	Period 1			Period 2			Period 3			Period 4		
	L	I	C	L	I	C	L	I	C	L	I	C
Poor end user acceptance	1	4	4	2	4	8	4	4	16	2	3	6
Legal risk	1	2	2	1	2	2	1	2	2	2	2	4
Methodology and tools	1	2	2	2	2	4	2	3	6	1	2	2
Operation issues	2	3	6	2	3	6	4	4	16	2	3	6
Information security	1	2	2	2	2	4	2	2	4	3	3	9
Roles and responsibilities	2	3	6	3	3	9	2	2	4	1	2	2
Budget overrun	0	2	0	4	2	8	2	2	4	4	2	8
Resource unavailability	1	2	2	1	4	4	1	4	4	1	2	2

Because the IT development project started with a preliminary study, the poor end user acceptance had a low likelihood and little impact in the earlier project phases. However, due to evolutions required by the key user group before the new application can go live, the risk of poor acceptance increased during the evaluation period 3. With the delivery of the software adjusted with the additional requests, the risk of poor acceptance became lower, but it was still higher with the increasing number of users.

The legal risk was stable during the whole project period and it was slightly increased at the final evaluation period. However, the human defects were high at the beginning with the inadequate external software developer team. This risk decreased after the change of the developers.

Concerning issues with SharePoint performances, the risk related to methodology and tools did not raise before period 2 but became critical between periods 2 and 3. Another type of risk related to methodology and tools had to be considered for data migration operations and integration with other existing applications for document management. Similarly, the risk of information security increased in the period 4 when the data migration and document sharing were performed.

The operation issues (of the technical issues – see Figure 4-13) reached a high level during the periods 2 and 3 due to the change of software developers and the difficulties in implementing the new functional architecture.

There was a high probability that the budget will be exceeded at the end of the period 2 because the quality of the first delivery was really poor. The risk went even higher when additional requests were requested by the key user group. However, because the organisation accepted to modify the initial budget, the impact was limited. Nevertheless, this risk became high when too much delay was reached at the end of the project.

The unavailability of business resources induced repetitive development of functionalities and was mainly involved in the development of Adonis2 (periods 2 and 3).

Then, the criticality index of all elementary expressions were normalised using Equation 3-8. The results are shown in Table 4-25.

Table 4-25. Normalised risk expressions for case study 3

Phases / Variables	Period 1	Period 2	Period 3	Period 4
Poor end user acceptance	0.75	0.50	0	0.63
Legal risk	0.88	0.88	0.88	0.75
Methodology and tools	0.88	0.75	0.63	0.88
Operation issues	0.63	0.63	0	0.63
Information security	0.88	0.75	0.75	0.44
Roles and responsibilities	0.63	0.44	0.75	0.88
Budget overrun	1.00	0.50	0.75	0.50
Resource unavailability	0.88	0.75	0.75	0.88

The elementary performance expressions for value and risk cannot be directly applied for decision support because they only indicate part of the overall performance. Therefore, an aggregation operation is necessary to generate the overall expression for both dimensions.

4.3.6 Aggregation phase

4.3.6.1 Criteria weighting

The importance of each elementary performance expression depends on the evaluator preference and the specific decision context. While transforming numerous elementary expressions into one global result, their relative importance is expressed by the weights that are assigned to each element. These weights are generated through a pair-wised comparison for all elementary values or risks at the same level of the breakdown structure (as detailed in Chapter III, Section 3.3.2).

In this case study, the results of criteria weighting for the dimensions of value and risk are presented in Table 4-26.

Table 4-26. Criteria weighting for elementary values and risks for case study 3

Performance dimensions	Elements (level 1)	Normalised weights	Elements (level 2)	Normalised weights	Elements (level 3)	Normalised weights
Value	User experience	0.40	-	-	-	-
	Utility	0.19	Accessibility	0.75	-	-
			Acceptance	0.25	-	-
	Quality	0.31	Reliability	0.83	-	-
			Support	0.17	-	-
	Productivity	0.09	-	-	-	-
Risk	Poor end user acceptance	0.31	-	-	-	
	Planning defects	0.39	Legal risk	0.09	-	-
			Technical issues	0.69	Methodology and tools	0.23
					Operation issues	0.65
					Information security	0.12
			Roles and responsibilities	0.22	-	-
	Budget overrun	0.20	-	-	-	-
	Resource unavailability	0.10	-	-	-	-

To avoid random judgments with low consistency, the consistency index is verified at each level where more than two normalised weights are involved. The results are presented in Table 4-27.

Table 4-27. Consistency index for normalised weights for case study 3

Performance dimensions	Consistency index (level 1)	Consistency index (level 2)	Consistency index (level 3)
Value	0.08	-	-
Risk	0.09	0.05	0.01

As all consistency index ratios are less than 10%, it is considered that the normalised weights in Table 4-26 are not random. They can be applied to the aggregation operation.

4.3.6.2 Aggregation operation

Considering the comparison made in case study 2, it is considered that the 2-additive Choquet integral operator is supposed to be more accurate for developing the aggregation results. So, it is used to generate the overall value and risk in this case study. However, the aggregations at lower levels are still developed using the weighted arithmetic sum in order to limit the complexity of the operation. The overall value and overall risk of this IT development project are presented in Table 4-28 and Table 4-29.

Table 4-28. Overall value generated with 2-additive Choquet integral operator for case study 3

	User experience (EV1)	Utility (EV2)	Quality (EV3)	Productivity (EV4)	Overall value
Period 2	0.50	0.23	0.89	0.60	0.39
Period 3	0.23	0.23	0.10	0	0.06
Period 4	0.50	0.38	0.89	0.60	0.44
v_i	0.40	0.19	0.32	0.09	-
I_{ij}	I_{12}	I_{13}	I_{14}	-	
	0.21	0.13	0.45		
	I_{23}	I_{24}	I_{34}		
	0.46	-0.29	0.04		

Table 4-29. Overall risk generated with 2-additive Choquet integral operator for case study 3

	Poor end user acceptance (ER1)	Planning defects (ER2)	Budget overrun (ER3)	Resource unavailability (ER4)	Overall risk
Period 1	0.75	0.71	1	0.88	0.61
Period 2	0.50	0.64	0.50	0.75	0.40
Period 3	0	0.41	0.75	0.75	0
Period 4	0.63	0.72	0.50	0.88	0.44
v_i	0.31	0.39	0.20	0.10	-
I_{ij}	I_{12}	I_{13}	I_{14}	-	
	0.09	0.01	0.69		
	I_{23}	I_{24}	I_{34}		
	0.70	0.41	0.09		

As shown in the above tables, v_i are the Shapley parameters that represent the relative importance of each elementary expression. They are identified in the criteria weighting step. Based on the value breakdown analysis, the overall value of this IT development project contains four elementary values (EV) at the lower level. They are: user experience (EV1), utility (EV2), quality (EV3) and productivity (EV4). Similarly, the risk breakdown structure also shows that the overall risk in this project is further expressed by four elementary risks (ER) at the lower lever. They are: poor end user acceptance (ER1), planning defects (ER2), budget overrun (ER3) and resource unavailability (ER4). Therefore, I_{ij} are interaction parameters to show the interactions between each pair of these elementary expressions within the same performance dimension.

Finally, the overall cost, value and risk expressions in each performance evaluation period are summarised in Table 4-30 to indicate the comprehensive performance of this IT development project.

Table 4-30. Overall performance expressions for case study 3

	Period 1	Period 2	Period 3	Period 4
Overall cost	0.94	0.38	0.39	0
Overall value	-	0.39	0.06	0.44
Overall risk	0.61	0.40	0	0.44

4.3.7 Graphical decision support

The overall performance expressions at different phases of the project are presented in a 3D graph to the project owner and used by the business project manager and IT project manager to monitor and control the project. Figure 4-15 shows the graphical expressions for all evaluation periods. From these points, the decision makers can review the state and evolution of the project regarding the three selected performance dimensions: cost, value and risk.

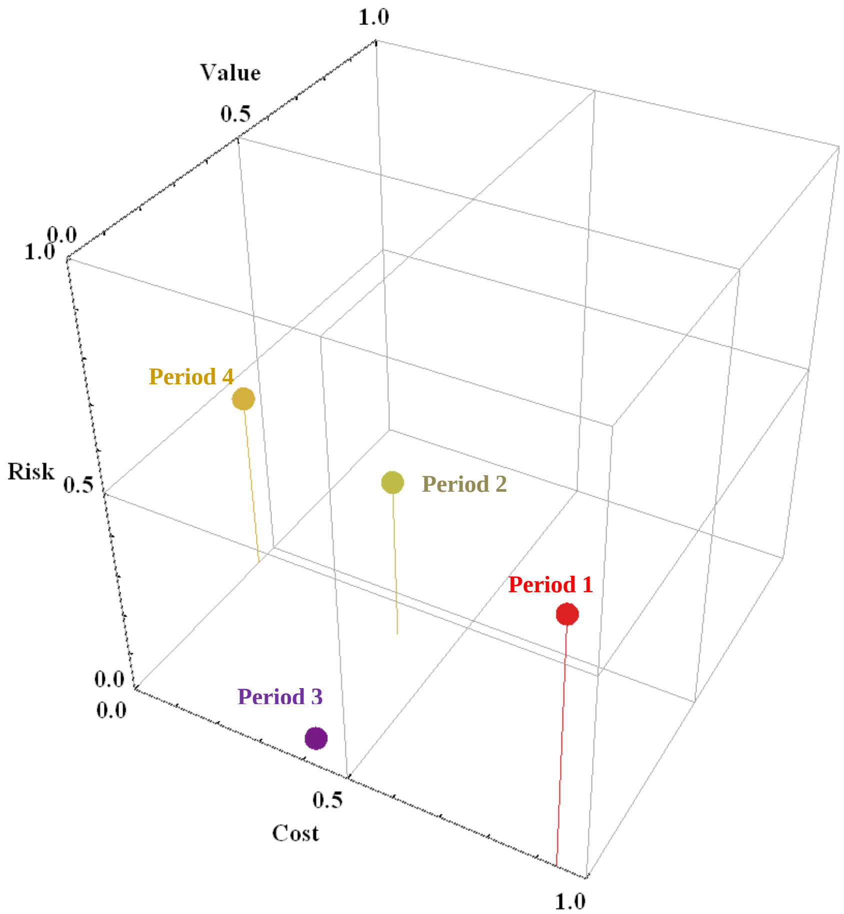


Figure 4-15. Plot of overall performance expressions for all evaluation periods of case study 3

In the evaluation period 1, the project cost refers to the spending of the preliminary study. Less risk and value were involved when the project was in the initial stage. So, the overall performance has the highest performance expression in cost and risk, while no value was generated. The project is fine.

During the second evaluation period, the performance expression was significantly decreased on the axis of cost, because the deliverables of the first construction iteration from the initial external software developers were below expectations. This resulted in a loss of spending. The project expenditure exceeded the initial budget (point "0.5" in the axis of cost). This also increased the project risk with delay of delivery date. The first overall value expression was generated with the first release of Adonis2. It could be rated as average. With the change of development team, the project owner could decide if the initial budget can be modified to continue the project with the new external developers or if the project should be stopped. Finally, the project owner decided to add additional funding and continue the development of the application with a new external development team because there was a high internal demand for the new system.

In period 3, serious technical issues were involved with the version 1_2 of Adonis2. Therefore, the performance expression became much worse in terms of risk. Also, the value expression was rather low due to poor user acceptance (slow response time with many blocking bugs). The cost expressions stayed constant, because no programming was developed during this period. Nevertheless, the project owner with the management team decided to continue the project and made decisions on necessary adjustments to improve user satisfaction and control further spending and delay.

At the last evaluation period (final version of Adonis2), the system performance (value) significantly improved, the risks were reduced but the final expenditure was still more than the modified budget because of the many additional modifications requested. So, the overall cost expression dropped to “0” while the risk and value expressions increased.

4.3.8 Discussion

This case study deals with decision problems in monitoring and control of an IT development project. In this context, it is necessary to perform several performance evaluations at different phases along the project life history. They provide the evaluator with status snapshots on the evolution of the project cost, value and risk. They can be used for decision making on future adjustments to be made to ensure the correct achievement of objectives.

The performance measurements performed at each stage were made on real data obtained from the project. The analysis has been made for four milestones of the project which required assessment of the status of the project. The number of measurements is decided by the management of the project and depends on the necessary decision points in the project. If many measurement points are made, the trajectory of points obtained show the evolution of the project and the impact of decisions on the evolution of each axis

In addition, it is assumed that the individual breakdown structure and the evaluation criteria remain constant along the different phases in the case study to limit the complexity of analysis. However, for more complex cases the breakdown structures, the evaluation criteria and the weights for each elementary performance expression should be reviewed for each measurement, because one performance variable can be involved in several phases with different importance. To ensure the accuracy of the evaluation results, the performance elements (i.e. variables or the breakdown analysis), which are generated at the identification phase, should be adapted at the beginning of each performance measurement.

4.4 Conclusions

In this chapter, three case studies have been developed to test the proposed methodology in different decision contexts. The first two cases, which were applied to supplier selection and building construction projects, have illustrated the application of the BCVR methodology in terms of decision support with a single performance evaluation on one and multiple dimensions of the BCVR approach. A mixed performance expression with numeric and linguistic variables has also been illustrated on these analyses. The third case dealt with management of various phases of a difficult IT development project to illustrate the application of the proposed methodology to performance evaluation for project monitoring and control. These case studies have shown the practical applicability of the proposed methodology to different kinds of business problems.

This BCVR methodology provides decision makers with an efficient methodological framework that is able to comprehensively evaluate with limited complexity the overall performance of a system, project or process. The methodology is instrumented with mathematical tools to integrate both qualitative and quantitative elementary performance expressions into aggregated quantitative expressions to support performance evaluation. Finally, it includes graphical facilities to present the overall performance expressions to ease decision making process and support visual management.

GENERAL CONCLUSIONS AND PERSPECTIVES

Considering the requirement to simultaneously satisfy several stakeholder objectives in the context of industrial project (or system) management, the performance should be comprehensively evaluated to ensure the correct accomplishment of objectives. Nowadays, due to a highly competitive environment, decision making should be performed over a shorter period with more varied needs from involved stakeholders. In addition, higher complexity of project environment results in a growing proliferation of various types of evaluation indicators. This increases the complexity in information collection and computation. Therefore, it is necessary to develop a more efficient and effective methodology to help evaluators and analysts in carrying out performance evaluation and decision support tasks.

It should also be noted that the performance of an industrial project (or system) is multi-dimensional (multi-viewpoint, multi-level and multi-criteria) and relative (depending on the evaluation period and the measurement method). These characteristics should be taken into consideration in performance evaluation. Otherwise, the performance expression is neither complete nor accurate.

After a thorough literature review on existing methodologies for performance measurement and management in Chapter I, it has been concluded that few of them can meet these requirements. Therefore, improvement can still be introduced in methodologies for performance evaluation and decision support. Based on the previous Ph.D. thesis of Shah (2012) on value-risk based performance evaluation, the work presented in this doctoral report has proposed and described a performance measurement and management methodology based on four dimensions: benefit, cost, value and risk (BCVR).

In the current research, *benefit* is defined as a qualitative list of potential advantages or gains for a stakeholder compared to an objective that is set beforehand for the realisation of an industrial project or system. *Cost* refers to total expenses for the production, distribution and acquisition of the final result (a product, service or deliverable) of an industrial system. *Value* is described as the degree of satisfaction of a set of stakeholder expectations or needs, expressed by the appreciation level of a number of performance indicators. *Risk* means the likelihood and consequence of an event occurrence impacting the achievement of some of the different stakeholder objectives.

Regarding the current business environment, it is considered that the performance of an industrial system can be comprehensively expressed and evaluated by means of these four performance dimensions which are usually categorised into two pairs. Cost and benefit have been largely studied and are often analysed together (for example, using the cost-benefit analysis) in practice. Value and risk, although widely studied separately, can be elaborated in an integrated way for performance evaluation. Although it is considered that the four dimensions are orthogonal at a broad level because they are analysed and evaluated separately, they can however interact at the basic level by sharing common elementary variables, as suggested in Figure 5-1. For instance, project delay can be a factor that can negatively impact user satisfaction and budget overrun risk, thus impacting the value and risk axes.

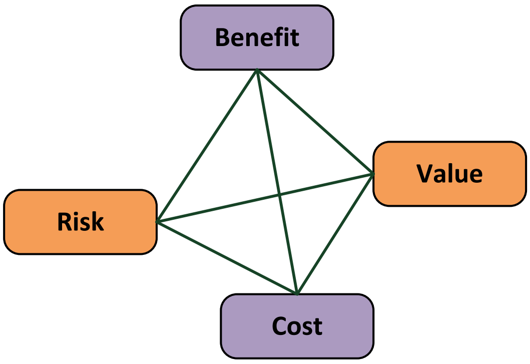


Figure 5-1. Performance dimensions of the BCVR methodology

Starting from these observations, the main objective of the Ph.D. thesis is to propose an operational, efficient and flexible performance evaluation and decision support methodology with limited complexity. Its aim is to help decision makers to perform opportunity evaluation for several decision alternatives (decision support), to evaluate the performance of a system/project/process at a certain specific evaluation period (performance evaluation) and to monitor execution of an ongoing process/project (project monitoring and control) in various industrial decision contexts.

To develop the methodology, the following tasks were performed in this Ph.D. research work:

- **Analysis of the key concepts**

  The key concepts of "benefit", "cost", "value" and "risk" are widely used in various research disciplines. Different definitions result in significant interpretation differences in terms of measurement and management. So, the first part of this Ph.D. work refers to analysis of these elements to build the basis for the BCVR based methodology. The deliverables of this part are:

  a) Adapted definitions for each BCVR axis regarding the comprehensive performance expression with consideration of both financial and non-financial aspects. The financial performance is expressed by cost dimension (total expenditure) and the non-financial performance is expressed in terms of benefits (potential advantages), value (stakeholder satisfaction) and risk (negative impact on objective achievement).

  b) Individual conceptual models to present the key elements and their relationships for performance measurement and management. Because the dimension of benefit is only qualitatively analysed in the current research, this analysis was applied to the three CVR axes which can be quantitatively analysed in the current research. It can be concluded from these models that the overall project cost, value and risk are directly measured through a top-down breakdown structure and that elementary performance expressions are integrated into overall expressions through aggregation operations.

c) Cost and risk classifications along different categories of project management processes. They are applied as checklists to help the evaluator or analyst to identify elementary costs and risks regarding the particular decision context of a specific problem.

The first part of this doctoral work provides the key concepts for the development of the BCVR based performance evaluation methodology. They describe the overall performance of an industrial project from multi-viewpoint, multi-level and multi-criteria by assessing the four selected performance dimensions. However, the industrial performance is also relative over time, which should be also taken into consideration in the proposed methodology. Therefore, an analytical framework for comprehensive performance expression was proposed as the second task of this Ph.D. thesis.

- **Proposition of an analytical framework for performance expression**

  To meet the multidimensional and relative characteristics of industrial performance, an analytical framework has been proposed. It contains three performance perspectives:

  a) *Stakeholders* that represent the points of view to be taken into account

  b) *Evaluation periods* that indicate the time or intervals at which an evaluation must be performed

  c) *Performance variables* that describe the components for performance evaluation with multi-level and multi-criteria for the problem at hand

  In addition, the analytical framework provides the evaluator or analyst with a flexible means to easily combine different elements in order to build up the adapted structure of the performance appraisal to face particular decision situations.

  Based on this framework, the evaluator or analyst is able to identify the basic elements for performance evaluation. The evaluation results should be generated through certain methods and tools. Therefore, the following task refers to the development of the BCVR based performance evaluation methodology.

- **Development of the BCVR based performance evaluation methodology**

  The proposed methodology consists of two parts: the global structure and the detailed operations.

  The global structure is a process made of four main steps:

  a) Identification of all relevant aspects in each performance perspective (stakeholders, evaluation periods, variables and criteria) to express the overall performance regarding the particular decision context, as well as the identification of the evaluation criteria to be used for each performance variable

b) *Quantification* of qualitative elementary performance expressions for selected CVR criteria

c) *Aggregation* to model the overall performance expression for each performance CVR dimension and

d) *Decision support* with visualised presentation of the overall performance expressions in a 3D graph to make easier the comparison of performance of different decision alternatives or to monitor project execution with performance evaluation at different project periods

The detailed operations of each phase of the methodology rely on a set of methods and tools for performance management and decision support. The identification phase proposes several methods for breakdown analysis, especially objective decomposition. The performance measurement and quantification phase combines different CVR assessment approaches to generate quantitative or qualitative elementary performance expressions and to transform qualitative expressions into numeric values, for instance using fuzzy numbers. These quantitative expressions are normalised with MAUT or deffuzzification methods and they are then integrated into overall expressions using weights generated by pair-wised comparison and aggregation operators such as weighted arithmetic sum and 2-additive Choquet integral. Finally, support to decision support is proposed using graphical visualisation of performance results in two or three dimension spaces.

- **Experimental applications with several decision contexts**

  The last task of this Ph.D. research work was to analyse several case studies to test the proposed methodology in different kinds of decision contexts. Three cases (supplier selection, construction project implementation and IT development project monitoring) have been analysed to test the application of the methodology to three types of decision problems: decision support, performance evaluation and project monitoring and control.

From these different pieces of work, it can be concluded that the BCVR based industrial performance evaluation methodology is applicable to different levels from key concepts analysis to applications to different decision situations. The main advantages of this proposed methodology are:

- **Taking into account the multi-dimensionality and the relativeness of industrial performance**

  The proposed analytical framework meets the two main characteristics of industrial performance stated in Chapter I. It ensures that the proposed methodology can be applied to generate comprehensive and reliable performance evaluation results in various decision situations.

- **Integrating the four BCVR performance dimensions into a common framework with adapted definitions and conceptual models**

  Based on industrial practices and previous research results, it is considered that the performance of an industrial project is globally expressed and evaluated by following the four selected performance dimensions. The literature review underlines that few of the existing performance measurement and management methodologies include all these dimensions. Therefore, the integration of BCVR into a common methodological framework can be considered as an improvement in the field.

- **Providing an efficient and practical methodology with global structure and detailed operations**

  This Ph.D. work has provided both a global methodological structure and detailed operations in each of its phases to guide the evaluator in carrying out performance evaluation and decision support exercises with the proposed methodology. The methodology relies on mathematical ways to integrate both qualitative and quantitative elementary performance measures into overall quantitative expressions. In addition, it proposes a graphical visualisation approach to help decision makers to evaluate performance of different alternatives or performance of one alternative at different periods according to their preference in a particular decision context. Considering results of three case studies, dealing with different types of decision problems, it is can be considered that the proposed methodology is efficient and operational in terms of performance evaluation and decision support.

- **Applicability of the methodology in different types of decision problems**

  From the case studies on supplier selection and construction project implementation, it appears that the proposed methodology can be used to compare different decision alternatives based on performance measures at a certain evaluation period (such as initialising stage or implementation phase).

  From the case study on monitoring an IT development project, it appears that the methodology can be applied to generate overall project performance expressions over time. Based on the evolution of the overall cost, value and risk, the online control decision can be made to improve performance and take decisions on the future stages of the project.

- **Flexibility of the BCVR methodology**

  The case studies have demonstrated that the BCVR methodology can be applied partially or fully, i.e. the evaluation can be made on the four axes together or on only three, two or even one, depending on the problem at hand to be solved. They have also showed that the methodology can be applied to a wide range of problems.

Conversely, although this document always focuses on the 4-tuple (benefit, cost, value, risk) as the four fundamental dimensions for performance evaluation, evaluators or analysts can consider additional or alternate dimensions, which may be components of the BCVR dimensions, regarding the specification of decision making.

For instance, in many projects the time dimension to monitor delays is crucial. While in this document, time was considered as a component of the value dimension because delays directly impact the satisfaction of stakeholders, time can be treated as a separate dimension in specific cases. Another example could be sustainability of manufacturing system or other types of systems. If sustainability can be defined quantitatively as we did for value, it can be processed as a separate dimension in the case of sustainability management projects.

To conclude, the BCVR based framework connects the different fundamental concepts about performance measurement and management commonly used to address the different issues described in the literature. The proposed methodology provides a useful methodological contribution to the performance evaluation and decision support discipline. This Ph.D. research work is based on both theories (such as project management theory and performance measurement theories) and approaches (such as modelling approaches and graphical decision support tools) within one methodological framework and they are applied to performance evaluation and decision support in different types of decision problems through case studies.

Concerning the perspectives, this Ph.D. research work can be extended in several directions. First, the application of the proposed methodology should be enriched for performance evaluation in other decision making contexts, such as product design, process planning (e.g. various process alternatives) or production system control. Case studies, applied to different industrial examples, will substantially enrich the proposed methodology for performance management and decision support in the context of process management. Although the methodology is developed and illustrated in the context of project management, it is considered that it can be extended to any type of industrial systems.

Another improvement of the methodology is the development of an IT tool which allows the automated computation regarding various operations of the whole evaluation process. The computations in the current work are individually generated in different tools. While applying the proposed methodology, it requires that the evaluator or analyst should have basic knowledge on the main theories and tools involved in each phase in order to select the appropriate combination. This results in difficulties in using the methodology in practice. If all operations can be integrated into one single IT tool, the application of the methodology could be more efficient for decision makers. The individual conceptual models expressed with UML class diagrams that are presented in Chapter II can be used as the basic elements for the development of such an IT tool. Gao (2014), a Masters student in the laboratory, developed a prototype of such an IT tool using EXCEL and Visual Basic for Applications (VBA) based on functional definitions developed in the first year of the Ph.D. programme. However, it was rated as too primitive to be reported in this document. A more professional tool should be developed.

Furthermore, the extension of the aggregated overall performance expressions with tolerable levels of cost, value and risk can be further exploited. Determining fixed maximum and minimum levels for each CVR performance dimension would be helpful for decision makers to evaluate the performance of one decision alternative. In addition, a more efficient or rational method could be proposed to determinate the bounds of the preference zones (as described in Chapter III, Section 3.4.1) for each evaluation axis of the graphical representation. Although this point was not in the scope of this Ph.D. research work, it can be one objective for further research. As it has been presented, the bounds are defined empirically by the analyst. They could be defined in a more systematic way taking into account previous experiences in decision making in a specific field (for instance using statistical analysis) or using precision criteria (such as thresholds or constraints) specific to that field. Finally, the performance variation (as discussed in Chapter III, Section 3.4.3) should be also integrated in the methodology to increase the accuracy of the overall performance expressions.

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APPENDIX A: CLASSIFICATION OF COSTS IN PROJECT MANAGEMENT

I. Costs related to the initiating process

1. External costs
    - Additional costs that are related to politics
        - Request for political support (for large projects)
        - Prevention of social and political instability
    - Economic costs due to financial instability
    - Fiscal costs (taxes)
    - Exchange costs related to currency fluctuations
    - Costs for relationship development with partners
        - Selection of suppliers and subcontractors
        - Exchange costs (for physical and IT flows)
        - Costs for communication and negotiation
        - Costs for partner replacement in case of incompetent
    - Unexpected costs due to natural disasters or exceptional events
2. Internal costs
    - Administrative costs related to internal exchanges
    - Costs for identification of needs
        - Marketing research
            - Opportunity study
            - Consulting expense
        - Costs of change due to lack of awareness of needs (for example, error in the study, insufficient expression from customer)
        - Costs for commercial obsolescence
            - Investment in infrastructure
            - Investment in new technology
    - Costs for restarting the project due to lack of experience

II. Costs related to the planning process

1. Technical costs
    - Costs for task analysis
        - Complete analysis
        - Task complexity estimation
        - Comparison with previous experience
        - Definition of resources and responsibilities
    - Costs for definition of project objectives and scope
        - Definition regarding the needs of the market, customer and enterprise strategy
        - Formalisation of the definition
        - Validation
    - Costs for the development of project scope statement
        - Budget analysis
        - Technical specifications
        - Technical performance estimation of the resources
    - Methodological costs
        - Technical estimation
        - Implementation of new standards or regulations
        - Modification and evolution
        - Planning tools

        - Deployment costs
2. Organisational and human costs
    - ➢ Establishment of the structure
        - Administrative expenses
        - Infrastructure investment
        - Expense for the provision
    - ➢ Construction of project team
        - Recruitment
        - Evaluation
        - Compensation
        - Training
        - Career management (for example, promotion)
    - ➢ Internal and external conflict management among stakeholders
    - ➢ Differential or opportunity costs associated with the decision
3. Costs related to the planning of resources
    - ➢ Resources definition
        - Study on resource availability
        - Outsourcing expenses
        - Expense related to security and logistics
    - ➢ Resources utilisation
        - Resource allocation
        - Internal projects management
        - Expense for solving unexpected issues

III. Costs related to the executing process

1. Instrumentation Costs
    - ➢ Costs for methods and tools
        - Utilisation of methods and tools (software licenses, maintenance and training)
        - Costs of modification due to inappropriate use of the concepts
        - Integration of tools in current system (expense of modification)
    - ➢ Costs for application of procedures
        - Communication studies
        - Potential supplies fees
        - Costs for modification of procedures
    - ➢ Costs of harm to health or damage to materials
2. Operation costs
    - ➢ Costs under development
        - Installation
        - Unexpected modification
        - Transportation and packaging fees
        - Direct labour charges
    - ➢ Costs related to the acquisition of resources
        - Infrastructure costs
        - Resources acquisition costs (purchasing costs)
            - Purchasing price
            - Incidental expenses of purchasing
            - Direct labour charges
            - Incidental expenses of procurement
        - Warehousing costs
            - Costs of storage space
            - Costs related to storage services
        - Costs of out of stock

- ➢ Supplier costs
  - Fees to change the suppliers
  - Costs related to the quality of material and delivery time
- ➢ Legal costs
  - Contractual fees

  Costs related to patents and licenses

3. Service costs
   - ➢ Subcontracting costs
   - ➢ External consultant costs

IV. Costs related to the monitoring & controlling process

1. Costs related to monitoring system
   - ➢ Choice of monitoring methods
   - ➢ Modification of the procedure
   - ➢ Control and steering
2. Detection & test costs
   - ➢ Charges of information emission
     - Costs for data updating
     - Costs for data formalisation
   - ➢ Information treatment
     - Costs for data collection and analysis
     - Processing tools
   - ➢ Tests
     - Unit tests
     - Module tests
     - Integration tests
3. Diagnostic costs
   - ➢ Problem estimation
   - ➢ Charge related to the proposed solution

V. Costs related to the closing process

1. Costs related to customers
   - ➢ Costs to secure customer and product information
   - ➢ Customer interruption costs
   - ➢ Costs of customer relationships management
2. Costs related to brand image
   - ➢ Distribution costs
   - ➢ Maintenance costs
   - ➢ After-sale services costs
   - ➢ Recycling costs
   - ➢ Costs related to treatment on environmental impacts
3. Training & communication costs
   - ➢ End user training
   - ➢ Promotion of end-result
   - ➢ Publicity and communication costs

APPENDIX B: CLASSIFICATION OF RISKS IN PROJECT MANAGEMENT

I. Risks related to the initiating process

1. Country risks (For some specific projects, for example, international investment and trade)
    - ➢ Political risks
        - National and international political risks
        - Intervention of public authorities
        - Social and political instability
        - Abandonment of political support
    - ➢ Fiscal risks
        - Double taxation
    - ➢ Exchange risks
        - Currency fluctuations
    - ➢ Economic risks
        - Inflation
        - Situation of economic crisis
        - Financial instability
    - ➢ Risk of natural disasters
2. Enterprise risks
    - ➢ Lacking knowledge of real needs
        - The customer deliver an insufficient project scope statement compared to its real demands
        - Errors in market research
    - ➢ Commercial obsolescence
        - Rapid evolution of the expectations
        - Delay in implementation
    - ➢ Partner relationships
        - Incapable suppliers and subcontractors
        - Poor coordination with and between subcontractors
        - Partners with potential competition
        - Misunderstanding between partners and with customers
    - ➢ Risks of inexperience
        - Lacking experience to comprehensively manager the project
        - Starting a project in an unfamiliar or hostile environment
    - ➢ Administrative risks related to internal changes

II. Risks related to the planning process

1. External risks
    - ➢ Regulatory risks on specifications
        - Enforcement of new standards
        - Lacking knowledge of the scope of specifications
2. Internal risks
    - ➢ Inaccuracy of tasks
        - Incomplete analysis of tasks due to lack of time or information
        - Underestimation of the complexity of tasks
        - Lacking previous experiences
        - Task overlapping
        - Poor definitions of recourses and responsibilities
    - ➢ Ambiguous objectives and scope definitions

- On the analysis of needs
- On the definition of customers
- With the enterprise's strategy
- Due to lack of formalization
- Due to lack of validation

➢ Inconsistencies with the project scope statement
- The data for project completion is too optimistic
- Insufficient budget
- The applied technical specifications are too ambitious
- The technical performance of the resources are overestimated
- Lack of consensus and standards

➢ Organizational and human risks
- Establishment of the structure and division of roles
- Decision making risks
  - Malfunctioning of the implemented mechanism
  - Behaviour of project actors
- Hierarchical risks
- Definitions of responsibilities
- Capitalization of expertise
- Conflicts between stakeholders
- Constitution of project team

➢ Technical and technological risks
- Underestimation of the technical complexity of the project
- Unavailable or poorly controlled process
- Frequent change and evolution
- Obsolescence of initial solutions
- Perfectionism
- Lack of creativity
- New standards and regulations
- Inherent limitations of planning tools

3. Risks related to resources planning

➢ Definition of resources
- Lacking knowledge on available potential
- Resource incompatibility
- Lacking consideration of security and logistics constraints
- Constrain of outsourcing
- Heterogeneity of the available resources

➢ Conflict management of resource utilization
- Allocation of inequitable resources
- No definition of the priority
- Competition between projects and within a project
- Appearance of unexpected problems

III. Risks related to the executing process

1. Instrumentation risks

➢ Regulatory and risks
- On the personal working conditions
- On the use of equipment

➢ Project management methods and tools
- Difficulties related to the use of methods and tools
- Inappropriate use of methods and tools

- Mismatch between necessary and available data
- Poor integration of the tools
- Abusive and incorrect use of the tools

➢ Application of the procedures
- Communication difficulties between research and implementation
- Ineffectiveness of the procedures
- Labour issues
- Internal contradictions
- Physical injury and material damage

2. Operation risks

➢ Risks during the execution
- Installation and start-up risks
- Unexpected modification during the execution
- Damage due to force majeure
- Risks related to transportation and packaging

➢ Risks related to the availability of the required resources
- Inadequate infrastructure
- Reliability of the procurement

➢ Suppler risks
- Technical failure (poor quality, delivery delay)

➢ Risk of insolvency (Legal risks)
- Contractual problems
- Patents and licences
- Various litigation

IV. Risks related to the monitoring & controlling process

1. Risks related to monitoring system

➢ Inadequate and/or non-formal monitoring methods
➢ Lack of evaluation criteria
➢ Inadequate monitoring indicators
➢ Lack of reporting
➢ Co-existence of several systems
➢ Control defects
➢ Security negligence

2. Late detection

➢ Emission of information
- Irregular and late update
- Inadequate support

➢ Information processing
- Non centralized information
- Poor definition of processing
- Dilution of responsibilities

3. Inaccurate diagnosis

➢ Underestimated problems
➢ Undetected causes
➢ Biased representation

4. Inappropriate responses

➢ Biased logic
➢ Excess delay
➢ Absence of managers

V. Risks related to the closing process

1. Risks related to customer

- Risks of future competition
    - Divulgation of confidential information
    - Resale of products or services that are designed from confidential information
- Insolvency risk (failure to meet financial commitments)
- Risks of abusive appeal on guarantee (because the banking centres better protect the buyer than the seller)
- Contract interruption risk (unilateral termination of the project by the customer)
- Insufficient involvement of the customer
- Customer that is too versatile or invasive

2. Risks related to brand image
    - Poor after sale service
    - Product delivery beyond the deadline
    - Indirect or intangibles damages
    - Direct and indirect environmental effects

EVALUATION DE LA PERFORMANCE ET AIDE A LA DECISION POUR LA GESTION DE SYSTEMES INDUTRIELS : METHODOLOGIE BASEE SUR BENEFICE-COÛT-VALEUR-RISQUE

RESUME : La mesure et la gestion de la performance représente de sérieux défis aux praticiens et chercheurs en génie industriel et sciences de gestion pour une prise de décision efficace sur base d'informations intégrées, dynamiques et pertinentes concernant la satisfaction simultanée d'objectifs émanant de diverses parties-prenantes. Bien que nombreuses méthodologies et outils aient déjà été proposés, des progrès en la matière sont encore possibles pour aider les gestionnaires et les ingénieurs à prendre de meilleures décisions et ce, de manière plus systématique.

En considérant que la performance d'un système, projet ou processus industriel peut-être globalement évaluée en suivant quatre dimensions (bénéfice, coût, valeur et risque), cette thèse propose un cadre original et complet ainsi qu'une méthodologie opérationnelle afin d'appliquer des méthodes et outils d'intervention appropriés dans l'évaluation de la performance et l'aide à la décision au sein de projets industriels.

A l'aide de plusieurs exemples inspirés de cas industriels, ces travaux soulignent que la méthodologie proposée peut être le support de : l'évaluation de plusieurs scénarios de décision pour sélectionner la solution la plus appropriée, l'évaluation de la performance à toutes phases d'un projet industriel et le pilotage d'un projet en cours avec plusieurs points d'évaluation durant le cycle de vie.

Mots clés : Systèmes industriels, gestion de la performance, mesure de la performance, aide à la décision, gestion de projet, valeur, risque, ingénierie des systèmes

PERFORMANCE EVALUATION AND DECISION SUPPORT IN INDUSTRIAL SYSTEM MANAGEMENT: A BENEFIT-COST-VALUE-RISK BASED METHODOLOGY

ABSTRACT: Performance measurement and management represents serious challenges to practitioners and researchers in industrial engineering and management sciences for efficient decision making with integrated, dynamic and relevant performance information regarding simultaneous accomplishment of multiple stakeholder objectives. Although many methodologies and approaches have already been proposed, there is still room for new advances to go further in assisting managers and engineers to make better decisions in a more systematic manner.

Assuming that the performance of an industrial system, project or process can be comprehensively evaluated by four main dimensions (benefit, cost, value and risk), the thesis proposes an original and complete framework as well as an operational methodology to apply relevant supporting methods and tools for the sake of performance evaluation and decision support in industrial projects.

Using several examples based on industrial cases, the work emphasises that the proposed methodology can provide the support for: opportunity assessment of several decision alternatives to select the most appropriate one, performance evaluation at any phase of an industrial project and monitoring of an ongoing industrial project requiring performance evaluation at several phases along its life history.

Keywords: Industrial systems, performance management, performance measures, decision support, project management, value, risk, systems engineering

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