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LE RETRAVAIL EN CONCEPTION D'INGÉNIERIE DANS LES PROJETS DE DÉVELOPPEMENT DE PRODUIT : LE CAS D'UN FABRICANT D'EQUIPEMENT D'ORIGINE (FEO) CANADIEN

ENGINEERING DESIGN REWORK IN PRODUCT DEVELOPMENT PROJECTS: A CANADIAN OEM CASE STUDY

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Le retravail en conception d’ingénierie dans les projets de développement de produit : le cas d'un fabricant d'équipement d’origine (FEO) canadien

Engineering design rework in product development projects: a Canadian OEM case study

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Cette thèse a été évaluée par un jury composé des personnes suivantes :

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SUMMARY

Business organizations are goal-oriented entities seeking to keep their competitive advantage sustainable. Timely and cost-effective implementation of projects contributes to achieving their goals. However, organizations still struggle to efficiently manage their projects.

In product development projects, the project core relies on design engineering teams and processes because approximately 75 % of the product costs are defined by development engineering teams. In addition, among the challenges faced in engineering design processes is the engineering design rework of activities that were expected to have been done correctly the first time but that need, because of the identification of a problem, to be done again.

The literature review showed that rework in product development projects was understood by consulting companies mainly in terms of litigation processes rather than from an academic perspective. In addition, as far as the researcher is aware, no studies on the evaluation of the dynamics of rework in complex product development projects have been conducted. Therefore, the main objective of this research is to evaluate the dynamics of engineering design rework that negatively impacts the performance of complex product development projects.

The product development project environment is continuously changing. To understand the reality that rework is embedded in this environment, the research adopted an organizational becoming stance as its ontological perspective. In addition, because rework depends on the context and on the stakeholders' perspectives, the epistemological stance is interpretivism.

The research approach is inductive because this approach is intended to explore underdeveloped constructs. The qualitative methodological approach was adopted for this research, and the qualitative research design is the holistic single case study based on a single unit of analysis, i.e., a multibillion-dollar, highly complex aircraft development project.

The soft systems thinking methodology was chosen as the basis of the research data collection and analysis strategy. The data collection included participant observation, analysis of approximately 100 documents from the organization that was the subject of the case study, 42 semistructured interviews and 12 ad hoc meetings. The data analysis followed the three layers of the iceberg model, i.e., events, patterns and systemic structure. The layers correspond to the case study history (causal map and a rich picture), the identification of behavior patterns (system archetypes) and the dynamics of rework (causal loop model), respectively.

The systemic structure of the dynamics of rework in a complex product development project is summarized in three stages. First, the project scope and the product complexity were underestimated. Second, the managerial decision to overlap project phases and progress with knowledge gaps resulted in invalid project assumptions that initiated rework cycles. Third, the consequences of previous stages led teams to work with unfrozen information and asynchronously, thus initiating rework cycles that reduced their availability to work in collaboration.

The following recommendations are proposed as high-leverage actions to influence the dynamics of rework and improve project performance: institute a robust product requirement management process; manage experts’ availability throughout the product development project; challenge the reuse of previous product development information; ensure the clear visibility of the development activity sequence; and ensure the clear visibility of the maturity level of the information being exchanged between the interdependent product development teams.

The academic contributions of this research include feedback for the research streams identified in the literature review: traditional project management, the design structure matrix (DSM) and system dynamics modeling. The managerial contributions include the research methodology presented in this study to understand complex problems, the chain of causality concerning management decisions, the engineering design rework and the project performance, and the translation of the complex problem into organizational behavior.

SYNTHÈSE

Les organisations d'affaires sont des entités qui ont comme objectifs de maintenir leur avantage concurrentiel de façon durable, d’augmenter les ventes et leurs profits. Pour atteindre leurs objectifs, ils dépendent fortement des actions définies par leur stratégie. La mise en œuvre rapide et rentable des projets contribue à l'atteinte de leurs objectifs grâce à la prestation de services et de produits et à l'amélioration des résultats.

Cependant, même si les académiciens et les praticiens ont largement abordé le thème de la gestion de projet, les organisations ont toujours du mal à gérer de manière efficiente leurs projets et à les mener à bien dans les délais et le budget prévus. Plusieurs raisons qui impactent la performance des projets ont été étudiées, telles que le désalignement d’objectif entre les niveaux organisationnels stratégique et opérationnel, ainsi que le déséquilibre relatif au portefeuille de projets organisationnels.

Dans les organisations responsables des projets de développement de produits, l'inefficacité de la performance peut être aggravée en fonction du niveau d'incertitude relatif à l’atteinte des objectifs, ainsi que le niveau d'incertitude sur le processus de développement de produit. En outre, elle peut être aggravée en fonction de la complexité structurelle du projet, qui inclut le nombre de personnes, la quantité de services et de fournisseurs impliqués. De plus, étant donné que cela concerne les entreprises et que leur objectif est de générer du profit pour leurs actionnaires, la pression exercée pour réduire les délais de mise sur le marché et les coûts est un facteur important à ne pas négliger.

Dans les projets de développement de produits, l’essentiel du projet repose sur les équipes techniques et les processus d’ingénierie de conception, lesquelles sont généralement dictés aux attentes des performances du produit et non par la performance du projet, telles que le respect des coûts et des échéanciers. Par conséquent, même si la phase de développement du produit représente environ 5 % du coût du projet, 70% à 80% de la définition du coût du produit est défini par les équipes d'ingénierie de conception durant cette même phase. Cela confirme la pertinence qu’une attention particulière doit être portée au processus de conception. Parmi les défis auxquels sont confrontés les processus de conception dans les projets de développement de produits se trouve le ‘retravail’ de conception.

Le retravail est associé aux activités que l'on s'attend à faire correctement la première fois, et qui en raison de l'identification d'un problème, doivent être refaites à nouveau. Généralement, le retravail est considéré comme une activité normale et une caractéristique intrinsèque des projets de développement de produits, car ce type de projet suit une logique de processus créatif qui comprend de l'incertitude et l'évolution des connaissances. De plus, le retravail est une alternative permettant d’ajuster la conception du produit tout au long du projet, de sorte qu'une solution optimale alignée sur les exigences du projet peut être fournie à la fin.

Cependant, le retravail de conception a des effets négatifs sur la performance du projet de développement de produit, qui, dans le pire des cas, peuvent être catastrophiques. Le retravail peut consommer de 30 % à 50 % la capacité utile d'ingénierie, ce qui signifie que les équipes d'ingénierie peuvent dépenser jusqu'à la moitié de leur capacité à retravailler le concept du produit. Donc, le retravail est une source de gaspillage, par conséquent il doit être éliminé si l'on veut améliorer la performance du projet.

Lors des entrevues menées auprès des praticiens au cours de la recherche, il fût validé que le retravail de conception est une source de coût et de retards dans les projets de développement de produits. Le retravail de conception est attendu, mais il ne peut pas être entièrement anticipé et planifié. Afin de gérer le défi du retravail, les praticiens ont mentionné deux approches : l'une réactive, dans laquelle le retravail de la conception sera effectué lorsque le besoin de correction sera découvert, et l’autre proactive, la mise en place d’un processus de révision progressif avec des étapes de contrôle de qualité tout au long du processus de développement du produit, afin de réduire le temps de détection des défauts.

La recension de la documentation a montré que les études de retravail dans les projets de développement de produits sont principalement le résultat de firmes de consultation dans le cadre de processus de litige plutôt que par une investigation académique solide comme celle proposée par cette étude.

De plus, au meilleur de la connaissance de la chercheuse, aucune étude n'a été trouvée concernant l'évaluation de la dynamique du retravail dans les projets de développement de produit complexe. Même si la littérature a révélé que le corpus de connaissances sur le retravail a été largement étudié dans la littérature de la construction, des études récemment publiée reconnaissent le manque de connaissances systématiques concernant la dynamique du retravail, ce qui rend toujours difficile de proposer des généralisations et une prévisibilité pour résoudre le problème du retravail.

En ce sens, la présence du retravail de conception dans le projet de développement de produit est un véritable défi de gestion, car lorsqu’il perturbe le projet de développement du produit, il est coûteux et il contribue aux retards du projet. Examiner le retravail de conception, c'est-à-dire mieux comprendre ce phénomène, permet de proposer des recommandations pour l'atténuer et améliorer la performance du projet de développement de produits.

Pour cette raison, l'objectif principal de cette recherche est d'évaluer la dynamique du retravail de conception qui a un impact négatif sur la performance des projets de développement de produits complexes.

L'environnement du projet de développement de produit est une réalité qui change constamment. De plus, les changements proviennent de différentes sources et surviennent à différents moments du cycle de vie du projet. Afin de mieux saisir la réalité dynamique dans laquelle s'inscrit le retravail, cette recherche a adopté une position organisationnelle *becoming* en tant que perspective ontologique. De plus, le retravail dépend fortement de son contexte et ainsi que des différentes perspectives des parties prenantes, donc la position épistémologique adoptée par cette étude est l'interprétivisme.

L'approche de recherche adoptée est inductive, dans la mesure où cette approche cherche à explorer des concepts sous-développés ou des cas dans lesquels une observation complexe est requise. Le choix méthodologique qualitatif a été retenu, lequel est approprié, car la chercheuse doit comprendre les concepts sociaux d'une réalité. Par ailleurs, la conception de la recherche étant émergente, elle envisage de développer un cadre conceptuel enrichi.

La stratégie de recherche qualitative est l'étude de cas unique holistique. L'étude de cas est basée sur une seule unité d'analyse, soit le projet de développement de produit complexe, afin de comprendre la dynamique du retravail de conception dans un projet de développement du produit.

La méthodologie de la pensée systémique souple a été choisie comme base de la stratégie de collecte et d'analyse des données de la recherche, puis qu'il s'agit d'une approche holistique et qu'elle a été une alternative à la gestion de projet traditionnelle pour gérer la complexité et l'environnement changeant des projets. Elle permet d'identifier les structures et les patrons qui sont à la base des problèmes complexes, de sorte que, des actions engendrant un grand effet de levier puissent être appliquées pour produire les résultats souhaités.

La stratégie de collecte et d'analyse de données est organisée en trois phases. La collecte de données inclut deux de ces phases et comprend les données recueillies provenant de sources multiples, comme l'observation participante, l'analyse de la documentation et des entrevues semi-structurées. L'analyse des données se fait en une seule phase, suite aux entrevues. L'analyse des données comprend la conception d'une carte causale, l'identification des archétypes de systèmes, et enfin la proposition d'un modèle de boucle causale de la dynamique du retravail qui est le cadre conceptuel de la recherche et l'atteinte de l'objectif de la recherche.

La phase préliminaire et la phase de collecte des données de cette recherche comprennent 49 entrevues semi-structurées, une revue systématique de la littérature couvrant 93 documents scientifiques, 12 réunions ad hoc avec les professionnels impliqués dans l'étude de cas et l'analyse d'environ 100 documents de l'organisation de l'étude de cas.

L'analyse des données a suivi le modèle de l'iceberg. Le modèle de l'iceberg a permis de comprendre la dynamique du retravail à partir de trois couches de l'iceberg, soit les événements, les patrons et la structure systémique. Les couches correspondant respectivement à l'histoire de l'étude de cas, l'identification des patrons comportementaux et la dynamique du retravail.

La couche des événements comprend la compréhension holistique du contexte du problème de gestion, les faits principaux, les parties prenantes impliquées, les décisions prises et les options disponibles. La carte de causalité et l'image riche sont les techniques de la pensée systémique souple utilisées comme moyen de représenter les événements des études de cas qui ont été recueillis pendant la collecte des données.

La couche des patrons représente la perspective d'une compréhension plus profonde de la dynamique du retravail. Les archétypes systémiques sont utilisés dans la mesure où ils sont des modèles génériques de comportements précédemment identifiés dans la littérature. Ainsi, quatre modèles ont été construits à partir de deux structures d'archétypes de systèmes identifiés dans les données recueillies. Les modèles sont résumés ci-dessous.

Modèle de mentalité de réutilisation : le contexte contraint du projet a conduit l'organisation à proposer une solution rapide de mise sur le marché basée sur une version antérieure du produit. Toutefois, la mentalité de réutilisation associée au besoin d'un produit concurrentiel a mené à une compréhension évolutive de la portée réelle du projet, ce qui a déclenché des activités de retravail et affaibli la capacité de l'organisation à livrer le produit dans les délais et au coût prévus.

Modèle de chevauchement des phases : la nécessité d'offrir une solution rapide de mise en marché associée à la mentalité de réutilisation a conduit l'organisation à chevaucher les phases de développement des produits. Ainsi, les équipes travaillaient de façon asynchrone et/ou avec des informations non gelées, ce qui a déclenché des activités de retravail, perturbé le processus de développement du produit et réduit la capacité de l'organisation à livrer le produit dans les délais et au coût prévus.

Modèle de la meilleure estimation : l'écart des connaissances est plus grand dans les phases préliminaires du projet et se réduit au fur et à mesure que le projet évolue. Toutefois, en raison de la pression exercée par le délai de mise en marché, la décision a été prise d'aller de l'avant avec les meilleures hypothèses. Les activités de retravail ont été déclenchées lorsque des hypothèses se sont révélées invalides, ce qui a perturbé le processus de développement du produit et réduit la capacité de l'organisation à livrer le produit dans les délais et les coûts prévus.

Modèle des adversaires accidentels adapté : la relation gagnant-gagnant entre les fournisseurs et l'organisation s'est érodée par les exigences supplémentaires nécessaires pour assurer un produit compétitif. Cela a déclenché des activités de retravail et réduit le profit du fournisseur. Ainsi, l'avancement du projet dépendait de la résolution des conflits commerciaux. De plus, la collaboration réduite entre les parties a conduit à des solutions techniques pas forcément optimales, ce qui a déclenché des activités de retravail.

La couche de structure systémique représente le mécanisme qui donne origine aux résultats des couches précédentes et elle représente la réalisation du but ultime de cette recherche. Le modèle de boucle causale représente la structure systémique de la dynamique du retravail dans un projet de développement de produit complexe et résume les principales variables et les relations de rétroaction entre les variables identifiées dans l'étude de cas.

Les principales variables révélées dans la dynamique du retravail sont l'exécution asynchrone du travail de l'équipe de développement, le travail collaboratif, la disponibilité des professionnels du développement de produits en temps opportun, la reconnaissance de la complexité du produit, les hypothèses invalides, la réponse rapide au marché, la mentalité de réutilisation, le progrès avec la meilleure estimation, le chevauchement des phases, le travail avec des informations non gelées, les litiges commerciaux des fournisseurs ainsi que le concept optimale du produit.

La structure systémique de la dynamique du retravail dans un projet complexe de développement de produit se résume en trois étapes. Premièrement, la portée du projet et la complexité du produit ont été sous-estimées parce qu'elles comptaient beaucoup sur la réutilisation des informations d'une version antérieure du produit. Deuxièmement, la décision de la direction, renforcée par l'information sur l'étape précédente, consistait à chevaucher les phases du projet et de progresser même avec des lacunes des connaissances. Pendant ce temps, au fur et à mesure que le projet avançait, la complexité réelle du produit se révélait, ce qui invalidait certaines hypothèses du projet et déclenchait des cycles de retravail. Troisièmement, les conséquences des étapes précédentes ont conduit les équipes à travailler avec des informations non gelées et de manière asynchrone, ce qui a réduit la disponibilité des membres de l'équipe à travailler en collaboration et a déclenché encore plus de cycles de retravail.

Le cadre conceptuel final de cette étude englobe la dynamique du retravail dans un projet de développement de produit complexe. Dans cette perspective holistique, issue des données collectées et analysées tout au long de cette recherche, certaines recommandations sont proposées en tant que des actions offrant un grand impact pour influencer la dynamique du retravail et améliorer la performance du projet. Elles se décrivent comme suit :

Exécuter un processus robuste de gestion des exigences du produit ; gérer la disponibilité d'experts en développement de produits dans les phases initiales du projet ; remettre en question les informations sur le développement des produits précédentes pour vous assurer que seules les informations à valeur ajoutée sont réutilisées ; éviter le chevauchement excessif des phases de projet ; impliquer plus en amont les équipes qui seront requises en aval car elles peuvent fournir des précieuses informations plus tôt dans le processus ; assurer une visibilité claire de la séquence des activités de développement et du niveau de maturité de l'information aux équipes interdépendantes de et assurer qu’elles progressent au même rythme au cours de la phase du projet.

Trois contributions théoriques de cette recherche sont mises en évidence :

La première concerne le volet traditionnel de la recherche en gestion de projet qui néglige les interdépendances et l'environnement changeant du projet. La contribution de la recherche a permis de démontrer que le traitement de ces éléments est essentielle pour gérer avec succès des projets de développement de produits complexes ;

La deuxième concerne le courant de recherche DSM. Même s'il vise des architectures optimales de processus de développement de produits, il néglige les décisions managériales tout au long du cycle de vie du projet. La recherche a permis de démontrer que les décisions de gestion fondées sur une mauvaise perception de la portée du projet et de la complexité du produit ont contribué à perturber le processus de développement du produit ;

La troisième concerne le volet de recherche sur la dynamique de système, pour lequel la chercheuse n'a trouvé aucune étude publiée à ce jour sur l'évaluation de la dynamique du retravail dans le cadre de projets de développement de produits complexes. La contribution de la recherche consistait à fournir un modèle de boucle causale de la dynamique du retravail appuyé par l'identification d'archétypes de systèmes reconnus.

Trois contributions managériales de cette recherche sont mises en évidence :

La première a un lien avec la méthodologie de recherche qui utilise des techniques de pensée systémique souple. Elles ont permis une compréhension holistique de la dynamique du retravail, ce qui s'est traduit par un moyen éprouvé pour recueillir et analyser les données dans un environnement organisationnel ;

La deuxième concerne la chaîne des causalités à l'aide de l'outil de carte de causalité créé à partir de trois sources de preuves : l'observation participante, l'analyse documentaire et les entrevues semi-structurées. La chaîne de causalités a présenté les explications des effets à court et à long terme des décisions de gestion qui ont entraîné du retravail et qui ont eu une incidence négative sur la performance du projet mais aussi positive sur la qualité du produit ;

La troisième concerne les événements traduits en comportements organisationnels permettant une meilleure compréhension de la dynamique du retravail. Les structures systémiques donnent origine à des patterns et à des événements. Reconnaître ces structures systémiques favorise l'identification d'interventions engendrant un grand effet de levier pour résoudre ou atténuer la présence du retravail de la conception technique dans les projets de développement de produit complexe.

Par conséquent, cette étude a atteint ses objectifs initiaux et a apporté des contributions théoriques et managériales significatives.

RÉSUMÉ

Bien que le thème de la gestion de projet ait été largement abordé dans la littérature scientifique et professionnelle, les organisations ont toujours du mal à gérer efficacement leurs projets de développement de produit complexe. Parmi les causes qui contribuent à la mauvaise performance des projets, le retravail de conception est un véritable défi managérial. En effet, la nécessité d'ajuster le produit en développement, en fonction des évolutions des besoins des clients et de la compétition, est source de perturbation. L'objectif de la recherche est de mieux comprendre la dynamique du retravail de conception. La méthodologie de la pensée systémique souple a été choisie pour la collecte et l'analyse des données. La dynamique du retravail d'un projet de développement d'avion a été ainsi modélisée et décrite dans un modèle de boucle causale. Les variables identifiées dans le modèle comprennent : exécution asynchrone du travail des équipes, travail collaboratif, disponibilité en temps opportun d'experts, reconnaissance de la complexité du produit, hypothèses invalides, réponse rapide au marché, mentalité de réutilisation, progrès avec la meilleure estimation, chevauchement des phases, travail avec des informations non gelées, litiges commerciaux avec fournisseurs, et concept optimal du produit. Les relations de rétroaction entre les variables identifiées dans le modèle sont représentées par la combinaison de quatre modèles basés sur deux archétypes de systèmes. Des actions pour influencer la dynamique du retravail et améliorer la performance du projet sont proposées, telles que l'exécution d'un processus de gestion des exigences du produit, la gestion de la disponibilité des experts, l'évaluation de la réutilisation des informations d'un projet précédent ainsi que la visibilité de la séquence des activités et le niveau de maturité des informations échangées par les équipes interdépendantes de développement produit.

Mots-clés : aviation, dynamique du retravail, performance du projet, pensée systémique souples, problème complexe

ABSTRACT

Although project management has been extensively discussed by academics and practitioners, organizations still struggle to efficiently manage their complex product development projects. Among the causes that contribute to a project's poor performance is engineering design rework, which is a management problem because it is necessary to adjust the product being developed at the same time that the development process is being disrupted due to the knock-on effects. The research objective is to evaluate the dynamics of engineering design rework that negatively impacts the performance of complex product development projects. The soft systems thinking methodology was chosen as the basis of the research data collection and analysis strategy. The dynamics of rework of a multibillion-dollar, highly complex aircraft development project were modeled based on the soft system dynamics methodology and depicted in a causal loop model. The main variables identified in the model are the asynchronous work execution of development teams, collaborative work, timely availability of product development professionals, product complexity recognition, invalid assumptions, quick-to-market response, reuse mindset, progress with best guess, phase overlap, working with unfrozen information, commercial disputes with suppliers, and optimal product concept and design. The feedback relationships between the variables identified in the model are represented by the combination of four models. The following high-leverage actions to influence the dynamics of rework and improve project performance are proposed: institute a robust product requirement management process, manage experts' availability throughout the product development project, challenge the reuse of previous product development information, ensure the clear visibility of the development activity sequence, and ensure the clear visibility of the maturity level of the information being exchanged between the interdependent product development teams.

Keywords: aviation, dynamics of rework, project performance, soft system thinking, complex problem

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LIST OF ABBREVIATIONS, ACRONYMS, INITIALS, AND SYMBOLS

CAD	Computer-aided design
CEO	Chief executive officer
CPM	Critical path method
DSM	Design structure matrix
EDR	Engineering design rework
OEM	Original equipment manufacturer
P	Product development project static factors
PD	Product development
PERT	Program evaluation and review technique
PMI	Project Management Institute
SAC	Shenyang Aircraft Corporation
SME	Subject-matter expert
US	United States
WBS	Work breakdown structure
x	Triggers of the dynamics of engineering design rework
y	Product development project performance
z	Product development project dynamic factors
Z	Product development project performance controlling factors
z’	Future state of z

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INTRODUCTION

Business organizations are goal-oriented entities that seek to keep their competitive advantage sustainable (Porter, 1998) by generating new sales and increasing their profits (R. G. Cooper, 2011, p. 14). To achieve their goals, they depend strongly on actions defined by their strategy (Daft, 2009, pp. 58-61). Timely and cost-effective implementation of projects contributes to achieving their goals through the delivery of services, products and improved results (Meredith & Mantel, 2011, p. 90; Milosevic, 2006).

Even though the project management theme has been extensively discussed by academics and practitioners (Padalkar & Gopinath, 2016), organizations still struggle to efficiently manage their projects and deliver them on time and on budget (PMI, 2018; Priemus, Flyvbjerg, & van Wee, 2008). Several reasons that impact project performance have been identified, such as objective misalignment between the strategic and operational organizational levels (Payette, 2016) and the organizational project portfolio balance (Archer & Ghasemzadeh, 1999).

In organizations that implement product development projects, project performance inefficiency can be aggravated by the level of uncertainty regarding the product being developed and the product development process (Turner & Cochrane, 1993). In addition, the project structural complexity, which includes the number of people, departments and suppliers involved, can aggravate the project performance inefficiency (Williams, 2005). In addition, as the objective of business organizations is to deliver profit, pressure for a reduced time-to-market and costs is an important factor that cannot be neglected.

In product development projects, the project core is the design engineering teams and processes, which are generally driven by product technical performance rather than by project performance in terms of as cost and schedule. Even though the product development phase represents approximately 5 % of the total project costs (Cao, Xiao, & Xing, 2011), 70 % to 80 % of the product costs are defined by the development engineering teams in this phase (K. Clark & Fujimoto, 1991; Kovacic & Filzmoser, 2014; Stark, 2005). Therefore, careful attention to the engineering design process is relevant. Among the challenges presented by the engineering design processes in product development projects is engineering design rework.

Rework refers to activities that are expected to be done correctly the first time, because of the identification of a problem, need to be done again (Love, 2002; Love, Smith, Ackermann, & Irani, 2019). Generally, rework is accepted as a normal and intrinsic feature of product development projects because this type of project is a creative process (Ulrich & Eppinger, 2016, p. 6) that involves uncertainty and evolving knowledge. Moreover, rework is an alternative to adjusting the product throughout the project so that an optimal solution aligned with the project requirements can be provided.

However, engineering design rework has negative effects on the product development project performance that in a worst-case scenario may be catastrophic. Rework can consume 30 % to 50 % of the engineering capacity (Fricke, Gebhard, Negele, & Igenbergs, 2000; Hamraz & Clarkson, 2015; Loch & Terwiesch, 1999; A. Maier & Langer, 2011), meaning that engineering teams potentially spend up to half of their capacity on rework. Thus, as rework is a source of waste, it should be eliminated if project performance is to be improved.

The interviews conducted with practitioners during the research validated the concept that engineering design rework is a source of costs and delays in product development projects. Engineering design rework is expected but cannot be fully predicted and planned (Karniel & Reich, 2009). To manage the rework challenge, the practitioners mentioned two approaches, one reactive – engineering design rework will be performed when the need for correction is discovered (Dostaler, 2010; Sterman, 1992)

– and the other proactive – quality gates throughout the engineering design process reduce the fault discovery time (Akkermans & van Oorschot, 2016; Love, Edwards, & Irani, 2008).

The literature review showed that rework in product development projects was understood by consulting companies mainly in terms of litigation processes (K. G. Cooper, 1980) rather than the type of robust academic investigation proposed by this study. In addition, as far as the researcher is aware, no studies on the evaluation of the dynamics of rework in complex product development projects have been conducted. Even though the literature review revealed that the rework body of knowledge has been widely studied in the construction literature (Love, Edwards, Watson, & Davis, 2010; Love & Irani, 2003; Love & Li, 2000), recent studies have recognized the lack of systematic knowledge concerning the dynamics of rework; thus it is still difficult to propose generalizations and predictions to address the rework problem (Forcada, Alvarez, Love, & Edwards, 2017; Yap, Skitmore, Gray, & Shavarebi, 2019).

The presence of engineering design rework in product development projects is a management challenge because it disrupts the product development project process, is costly and contributes to delays. Investigating engineering design rework to better understand this phenomenon allows the proposition of recommendations to mitigate it and to improve the product development project performance.

For this reason, **the main objective of this research is to evaluate the dynamics of engineering design rework that negatively impacts the performance of complex product development projects**. This objective is broken down into identifying the variables and the feedback relationships between the variables that comprise the dynamics. The literature review revealed four themes that may influence these dynamics, i.e., the process architecture, concurrent engineering, changing environment and system dynamics.

The product development project environment is continuously changing. In addition, the changes come from different sources and at different times in the project life cycle (Godlewski, Lee, & Cooper, 2012). Thus, in order to understand the dynamic reality that the object of this study is embedded in that environment, this research adopted an organizational *becoming* stance as the ontological perspective (Tsoukas & Chia, 2002). In addition, because the object of this study depends strongly on its context and on the different stakeholders' perspectives, the epistemological stance adopted is the interpretivism (Biedenbach, 2015).

The research approach is inductive because this approach is intended to explore underdeveloped constructs or cases in which complex observation is required (Love, Mandal, & Li, 1999). The qualitative methodology was chosen for this research because the researcher needed to comprehend the social constructs of a changing reality. Additionally, the research design is emergent because it aims to develop an enriched conceptual framework (Saunders, Lewis, & Thornhill, 2012).

The qualitative research design is the holistic single case study (R. K. Yin, 2003). The case study is based on a single unit of analysis, i.e., a complex product development project. The case study is analyzed from a holistic perspective in order to understand the dynamics of engineering design rework in a product development project.

The soft systems thinking methodology was chosen as the basis of the research data collection and analysis strategy because it is a holistic approach that has been used as an alternative to traditional project management to handle the complexity and changing environment of projects (Jackson, 2003). It supports the identification of structures and patterns that underlie complex problems (Senge, 1994) so that high-leverage actions can be applied to produce the desired results (Arnold & Wade, 2015; Sterman, 2000).

The strategy for the data collection and data analysis is organized in three phases. The data collection is divided into two phases and comprises data collected from multiple sources, such as participant observation, documentation analysis and semistructured interviews. The data analysis is a single phase that takes place after conducting interviews. The data analysis includes the conception of a causal map (Eden, 1994), a rich picture (Checkland & Poulter, 2010), the identification of system archetypes (Senge, 1994), and finally the proposition of a causal loop model of the dynamics of rework that is the conceptual framework of the research and the achievement of the research objective.

The dynamics of rework were modeled based on soft system dynamics methodology. The main variables identified are the development team asynchronous work execution, collaborative work, product development professionals' timely availability, product complexity recognition, invalid assumptions, quick-to-market response, reuse mindset, progress with best guess, phase overlap, working with unfrozen information, supplier commercial disputes, and optimal product concept and design. In addition, the feedback relationships between the variables are represented by the combination of four models based on two system archetype structures.

The academic contributions of this research include feedback for the research streams identified in the literature review: traditional project management, the design structure matrix (DSM) and system dynamics modeling. In addition, the managerial contributions include the research methodology presented in this study to understand complex problems, the chain of causality for management decisions, engineering design rework and project performance, and the translation of the complex problem into organizational behavior.

The document is structured as follows.

Chapter 1 introduces the managerial problem, which is the presence of engineering design rework in product development projects. Three game-changing product development projects and managerial problem validation from practitioners are presented to support the relevance of the managerial problem.

Chapter 2 presents the engineering design rework state of art resulting from an extensive literature review, followed by the discussion of four emerging themes, and the identification of three research streams. The chapter closes with the proposition of the preliminary conceptual framework and research objectives and questions.

Chapter 3 presents the research methodology undertaken for this study. The methodological position and the approach of the research are presented. Then, the research design and the strategy for data collection and data analysis are described. As the chapter closes with a discussion of the research design quality and the research ethical aspects.

Chapter 4 comprises the research results in three parts. The first part presents the data collected before undertaking the semistructured interviews and partial analysis results. The second part describes the semistructured interviews samples. The third presents the final data analysis of all the collected data.

Chapter 5 discusses the research results regarding the managerial problem and the literature review. The theoretical and managerial contributions are presented as well as future research paths. The strengths and weakness of the research close the chapter.

The conclusion, references and appendixes are presented last.

CHAPTER 1 - MANAGERIAL PROBLEM

The objective of this chapter is to introduce the managerial problem being investigated in this research. Historical project performance data are presented as evidence that organizations still struggle to manage projects efficiently. Hence, three game-changing product development projects are presented to illustrate the complex environment of this type of project. Among the reasons that prevent complex product development projects from achieving higher levels of project performance is rework, specifically engineering design rework. Therefore, the presence of engineering design rework in product development projects is the managerial problem being investigated in this research. Properly addressing this managerial problem is expected to improve project performance.

1.1 PROJECT PERFORMANCE

Business organizations are goal-oriented entities seeking to keep their competitive advantage sustainable (Porter, 1998) by generating new sales and increasing their profits (R. G. Cooper, 2011). To achieve their goals, they strongly depend on actions defined by their strategy (Daft, 2009, pp. 58-61). The timely and cost-effective implementation of projects contributes to achieving their goals through the delivery of services, products and improved results (Meredith & Mantel, 2011, p. 90; Milosevic, 2006).

Performance can be framed as doing the right things (effectiveness) and doing the things right (efficiency) (Drucker, 2011). To define performance levels, metrics to quantify the effectiveness and efficiency of actions should be defined (Neely, Gregory, & Platts, 1995). In the 1970s, financial indicators, such as return on investment and cost, were the main metrics to evaluate performance. In the 1980s, new dimensions of performance, such as quality and schedule, were considered (Nudurupati, Bititci, Kumar, & Chan, 2011). Currently, the stakeholder satisfaction, risk analysis and environmental changes beyond the project team's control are also performance dimensions (Serrador & Turner, 2015). Additionally, Kerzner (2011, p. 77) proposes four categories, business-based, project success-based, project-based and project management process, as shown in Table 1.1.

Table 1.1

Performance categories and metrics

Category	**Metrics**
Business-based	Return on investment, net present value, payback period, cost reduction, future opportunities, profitability, market share, sales growth rate
Project success-based	Benefits achieved, value achieved, goals achieved, stakeholder satisfaction
Project-based	Time, cost, scope, scope changes, quality, customer satisfaction with project performance, risk mitigation
Project management process	Continuous improvements, benchmarking, accuracy of the estimates, measurement, metrics targets

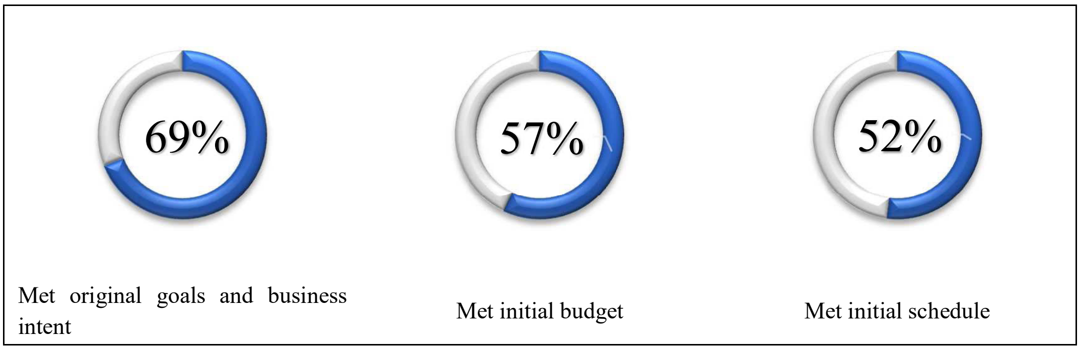
Source: (Kerzner, 2011, p. 77)

The project management discipline seeks to offer methods and tools to contribute to the delivery of improved project performance. Although project management best practices were popular among practitioners for more than 60 years and have been a research topic for approximately 15 years (Padalkar & Gopinath, 2016), organizations still struggle to manage projects efficiently and to deliver optimal business results. Evidence of the challenge regarding project performance can be observed in historical project performance data and case studies, as presented below.

A survey prepared by the Project Management Institute (PMI) involved 4455 project management practitioners who were asked to estimate the percentage of completed projects that met the original goals and business intent, met the initial budget and met the initial schedule. The results suggest that there is room for improvement, as only 69 % met the original goals and business intent, 57 % met the initial budget and 52 % met the initial schedule (PMI, 2018), as shown in Figure 1.1.

Figure 1.1

Project performance based on the PMI survey of 4455 practitioners



Source: (PMI, 2018)

Further evidence is presented in a study by Priemus et al. (2008, p. 15) of multibillion-dollar projects. The study pointed out that project cost estimates and cost overruns did not improve in the previous 70 years. The study covered projects in 20 countries over five continents, including public and private partnerships for infrastructure projects such as tunnels, bridges and railways.

Similarly, a study on the Olympic Games, covering the period between 1960 and 2016, found that all the Games in this time frame systematically overran the project budget with an average cost of 5.2 billion dollars. A staggering 47 % of the Games surpassed 100 % of the approved budget (Flyvbjerg, Stewart, & Budzier, 2016). A particular challenge of these projects is the schedule constraint, which is the immovable date of the event (Sato & Chagas Jr., 2014).

Regarding product development projects, in a project sample analyzed by R. G. Cooper (2011, p. 49), half of the product developments did not meet the profit targets, and one-third of them failed at launch. A survey by the Product Development and Management Association found that the product success rates remained stable at near 60 % (Kalluri & Kodali, 2014). According to Ulrich and Eppinger (2012, p. 6), few organizations are successful more than 50 % of the time.

1.2 PRODUCT DEVELOPMENT PROJECTS

To illustrate the complex environment of product development projects and some of the reasons that prevent them from achieving higher levels of project performance, three game-changing product development projects in the aviation industry are presented, followed by a discussion of common points among the delivered products as well as their poor performance in terms of time and cost. This section closes with the presentation of some causes already identified in the literature that contribute to the poor performance of product development projects.

1.2.1 Game-changing product development projects

Product development projects in aeronautical organizations must comply with strict certification regulation requirements and high quality and safety standards (Gudmundsson, 2014). As a result, the end products usually exceed the product performance requirements. However, when the project performance is considered in terms of cost and time, there is a notable difference between the estimated and actual values at the end of the project. To illustrate the challenging environment of a product development project, three game-changing product development projects in the aeronautical industry are presented and discussed, the Bombardier C Series, the Boeing 787 Dreamliner and the Airbus A380.

1.2.1.1 Bombardier C Series

The C Series was a product development project performed by the original equipment manufacturer (OEM) Bombardier. It was projected to be a quieter and lighter narrow-body commercial aircraft, consuming 20 % less fuel than its closest competitor products. To achieve these goals, Bombardier needed major system suppliers, such as Pratt & Whitney, which developed a more fuel-efficient and silent engine. In addition to the new engine, the aircraft incorporated many new technologies, lightweight composite materials and metal alloys, fly-by-wire flight control systems and design and manufacturing processes (Committee, 2013, p. 16; Owram, 2015).

According to a former technical leader who worked at Bombardier and Boeing, the C Series aircraft was a clean-sheet design, meaning it was not an incremental improvement of an existing aircraft platform. Moreover, he stated that Bombardier engineers did not have experience in developing such an innovative product (Owram, 2015). Consequently, the project faced technical problems, including complex issues with its major suppliers Shenyang Aircraft Corporation (SAC) (Larocque, 2013) and Pratt Whitney (Tomesco, 2016).

In addition to the technical problems, aviation experts stated that Bombardier faced leadership management problems related to the new chief executive officer (CEO) and a change of senior executives (Owram, 2015; Patriquin, 2016). At the direction of the new CEO, Bombardier undertook three product development projects concurrently (Figure 1.2): the C Series, the Learjet 85 and the new Global 7000/8000 (Owram, 2015; Patriquin, 2016). This concurrency created competing demands for engineering specialists and financial resources between the projects (Patriquin, 2016).

Figure 1.2

Bombardier product development projects between 2007 and 2018

			2007		2008		2009		2010		2011		2012		2013		2014		2015		2016		2017		2018	
Project	Start	Finish	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2	S1	S2
Learjet 85	October, 2007	October, 2015																								
C Series	July, 2008	July, 2016																								
Global	October, 2010	July, 2018																								

(Melo, 2019)

The C Series project delivered an outstanding product that exceeded the product performance requirements (Sorensen, 2015). However, the project management targets, such as cost and schedule, were overrun 69 % and 50 %, respectively (Owram, 2015). According to Dinsmore and Cooke-Davies (2005) projects are means to accomplish strategic goals and deliver profit for organization shareholders; therefore, achieving project management targets is important to enable an organization's competitiveness and market survival.

1.2.1.2 Boeing 787 Dreamliner

Boeing is an organization with more than 100 years of experience in designing aircraft. In 1996, Boeing acquired McDonnell Douglas, another experienced organization in the aeronautical industry. However, all the organizational experience did not enable it to avoid the occurrence of several problems during the development of the 787 Dreamliner. Again, project problems are related to product technical problems and management problems that affected the project time and cost targets. Like Bombardier's C Series, the Boeing 787 Dreamliner concept also aimed to reduce noise, emissions and approximately 20 % of fuel consumption (Gaynor, 2015).

One of the large product technical challenges was the use of composite material instead of aluminum in over 50 % of the design of the aircraft body (Nelson, 2009). Although composite material was not new, it had never been used to such an extent in an aircraft (Gaynor, 2015). In addition to the composite, the introduction of new avionic systems and fly-by-wire controls was also technically challenging. All of these aspects were new for the organization; thus, more time was needed for testing and reworking during the prototype and test phases, which was not anticipated in the project management planning (King, 2007; Shenhar, Holzmann, Melamed, & Zhao, 2016).

Concerning the managerial problems, for the first time in its history, Boeing outsourced the design and manufacturing of 11 major aircraft systems based on a new risk and revenue sharing contractual model (Gaynor, 2015; Shenhar et al., 2016). The global supply network comprised 700 suppliers, of which 70 % were not local (Shenhar et al., 2016); thus, the suppliers were spread all over the globe. Hence, different cultural backgrounds, languages, working standards, local government regulations and interdependent design elements added even more complexity to the supply network (Gaynor, 2015).

In addition, an aggressive four-year project schedule was imposed to develop a new highly innovative product and an assembly line ready to produce one Dreamliner every 3 days. The result was a highly innovative aircraft of which the final development cost was more than double the initial 40 billion dollars, and the delivery was approximately 3 years late (Shenhar et al., 2016).

1.2.1.3 Airbus A380

Another well-known product development project that resulted in a market-disruptor product was the double-deck A380 commercial jet. From the project management perspective, it did not achieve the initial project targets (King, 2007); for example, the estimated development project cost was approximately 13 billion dollars, and the final cost was approximately 25 billion dollars (N. Clark, 2006; Tsang & Segal, 2019).

The A380 was the most complex project that Airbus had ever designed and manufactured (N. Clark, 2006). The aircraft had a maximum capacity about 840 passengers (BBC, 2005). In addition to the gigantic size, its design included composite material and new hydraulic, electrical and avionics systems (N. Clark, 2006). Each A380 cost approximately U$270 million (Stark, 2005). A peculiarity of this enormous aircraft is that the airports that were expected to operate the A380, for example, those in Sydney, Australia (King, 2007), and Heathrow, England (BBC, 2005), needed to invest millions of dollars in infrastructure (Sato & Chagas Jr., 2014).

In January 2005, the A380 was unveiled during an official ceremony in the presence of the European and Airbus consortium leaders France, Germany, the United Kingdom and Spain; approximately 5000 invitees were present (Airbus, 2005). However, in June the same year, Airbus announced publicly that the delivery of the A380 would be delayed due to manufacturing problems (N. Clark, 2006). Ultimately, there was a 2-year delay.

The major technical problem was the preassembled electrical harnesses that were designed and manufactured at a German production site in Hamburg. The harnesses had the incorrect dimension: they were short. The failure was discovered during the assembly-line process in Toulouse, France, months after the harnesses had been manufactured and only after the harnesses had been routed in the aircraft. Consequently, a massive amount of inventory totaling several hundred kilometers of electrical wire had to be discarded (N. Clark, 2006).

Considering that the A380 has 1,150 different functions demanding approximately 100,000 different cables, the error was costly in terms of both time and money. Rework activities needed to be undertaken, including a complete redesign of the electrical harnesses from scratch. Among the identified causes was the fact that the German and French facilities were using different computer-aided design (CAD) software. Hence, the information about the electrical harness definition was incompatible between the development and production teams (N. Clark, 2006; Kerzner, 2014, p. 252; Nevison, 2013).

According to specialists, even though the problem was technical in nature, it was also a reflection of the managerial problems that Airbus was undergoing (Stark, 2007). Since its foundation in 1970, Airbus aimed to integrate several existing organizations from 4 European countries into the Airbus consortium and to surpass Boeing products (Richter, 2017, p. 3). The national rivalry between French and German top executives was evident during the A380 project, resulting in poor coordination and communication between the French and German teams (Nevison, 2013).

1.2.2 Game-changing product development projects conclusions

The game-changing product development projects discussed here had common points concerning the final product delivered and the project performance in terms of time and cost. The final products were recognized as outstanding technical advances. However, their project performance in terms of time and cost was poor, they cost much more than initially estimated and they were delivered years late, as summarized in Table 1.2.

Table 1.2 presents in detail the cost overruns and delays associated with each of the game-changing projects. The three projects' actual cost was more than 50 % over their initial multibillion-dollar budgets and required at least an additional 40 % completion time. These figures suggest that there is plenty of opportunity to improve project performance in terms of cost and schedule.

Table 1.2
Game-changing product development project cost overruns and delays

Project	**Budget [Bi US$] estimate**	**Budget [Bi US$] actual**	**Budget overrun**		**Project duration estimate [years]**	**Delivery delay**	
			[Bi US$]	**%**		**[years]**	**%**
Bombardier C Series	3.2 (Owram, 2015)	> 5.4 (Owram, 2015)	> 2.2 (Patriquin, 2016)	69	5	2.5 (Owram, 2015)	50
Boeing 787	40 (Shenhar et al., 2016)	80 (Shenhar et al., 2016)	> 40 (Owram, 2015)	100	4	3.3 (Shenhar et al., 2016) 3 (Owram, 2015)	82
Airbus A380	13 (N. Clark, 2006)	25 (Tsang & Segal, 2019)	~12	52	5	2 (Sato & Chagas Jr., 2014)	40

(Melo, 2019)

Table 1.3 summarizes some of the project life cycle milestones, such as project launch, first flight, certification and entry into service. Regarding entry into service, a delay of at least two years between the estimated and the actual year that the product was delivered occurred in all three cases.

Table 1.3

Estimated and actual game-changing product development project milestones

Project	Project Launch	First flight Maiden flight	Certification	Delivery Entry into service	
				Estimated	Actual
Bombardier C Series	07/2008 (Bombardier, 2008)	09/2013 (Bombardier, 2013)	12/2015 (Bombardier, 2015)	2013 (Bombardier, 2008)	07/2016 (Bombardier, 2016)
Boeing 787	04/2004 (Shenhar et al., 2016)	12/2009 (Shenhar et al., 2016)	08/2011 (Gaynor, 2015)	03/2008 (Shenhar et al., 2016)	09/2011 (Shenhar et al., 2016)
Airbus A380	12/2000 (N. Clark, 2006)	04/2005 (Stark, 2007)	12/2006 (Stark, 2007)	12/2005 (Stark, 2007)	10/2007 (Richter, 2017, p. 20)

(Melo, 2019)

Table 1.4

Technical and managerial problems presented in the projects

Project	Problems	
	Technical	Managerial
Bombardier C Series	- Composite airframes - Fly-by-wire controls	- Complex issues with major suppliers - Three product development projects being undertaken concurrently, resulting in competing demands for specialists and financial resources
Boeing 787	- Composite airframes - Avionic systems and fly-by-wire controls	- New partnership relationship/contracts with suppliers - Test fails, and more time is needed to solve the detected problems that were not considered in the planning
Airbus A380	- Gigantic size - Electrical harnesses were too short	- Poor coordination and communication between French and German Airbus facilities

(Melo, 2019)

The largely off-target results of the game-changing projects include technical and management challenges faced within the organizations during the project life cycles. Table 1.4 summarizes some of the technical and management problems identified in the game-changing projects.

It is possible to observe three similarities among the game-changing product development projects. First, the projects are a business process for the organizations, thus delivering the product to the market as soon as possible is a project requirement. Therefore, all three game-changing product development projects were challenged by an aggressive project schedule, as shown in Table 1.3. Second, the three projects involved a high level of uncertainty and risk related to the products being developed. They were disruptive products, comprising many new technologies, such as the use of composite materials in an extended aircraft area and the introduction of fly-by-wire technology. Third, the three projects were complex because their objective was to develop game-changing aircraft.

In addition to these similarities, other factors that may have contributed to poor project performance in terms of time and cost are concurrency between three product development projects undertaken within the same OEM, poor coordination and communication between facilities within the same OEM, and complex issues faced by the OEMs with major suppliers.

1.2.3 Poor product development project performance causes

According to (Williams, 2005) a compound of three main factors are the causes underling the poor performance of complex projects: the project complexity, uncertainty and tight time constraint, which are briefly discussed below.

The complexity is associated with the multitude of elements that make up the project as well as the interconnections between those elements (Williams, 2005). The elements of a project includes human resources, suppliers, activities and communication channels. In a product development project, those elements also include the product parts, systems and subsystems. One challenge concerning the complexity factor is that a change to one element will probably trigger a change in the elements connected to it (Jarratt, Eckert, Caldwell, & Clarkson, 2010).

The uncertainty of a project can be associated with the level of available information. According to the dimensions presented by Turner and Cochrane (1993), uncertainty can be related to how well defined the goals and methods in a project are. In a product development project, uncertainty concerns both the product itself and to the process to develop the product.

Considering that the product development project is a creative process that starts from a concept and finishes with a physical artifact (Ulrich & Eppinger, 2016, p. 6), the uncertainty decreases progressively as the project life cycle progresses and more information become available. However, it becomes a challenge when new information invalidates previous decisions, resulting in project changes (Karniel & Reich, 2011, p. 20).

Last, the tight time-constraint factor exists because the product development projects objective is to offer a product to be sold in the market (Kalluri & Kodali, 2014); thus, organizations seek to complete product development as quickly as possible (Belay, Kekale, & Helo, 2011) in order to keep or expand their market (Wysocki, 2011). However, the tight time-constraint can become a challenge when schedule-driven decisions neglects complexity and uncertainty. According to Yaghootkar and Gil (2012), a schedule-driven attitude can degrade an organization's capability to deliver a project on time.

In light of the three factors, it is notable that the tight time constraint is in opposition to the time needed to decrease the project uncertainties. By contrast, when the project uncertainties invalidate the initial assumptions or hypothesis, it triggers changes in the project that may trigger other changes due to the project complexity, increasing the amount of activities to be executed. Consequently, the increased number of activities may favor even more schedule-driven decisions due to the tight time constraint, which in turn overlooks the complexity and uncertainties of the project, restarting new vicious circles that contribute to the poor project performance results.

In addition to the three fundamental factors presented by (Williams, 2005) – project complexity, uncertainty and tight time constraint – Wysocki (2011) includes *change* as one of the challenges imposed by the contemporary dynamic project environment. The literature presents other studies that have investigated several topics that impact project performance. Table 1.5 lists some of them.

Among the topics presented in Table 1.5, **rework** is the main topic of interest of this research. Rework is within one of the seven types of waste in manufacturing identified by Taiichi Ohno applied to product development processes (Oppenheim, 2011, p. 19; Woschke, Haase, & Lautenschläger, 2016). It relates to activities that are expected to be done right the first time. However, due to problems such as improper planning or coordination, they fail and require rework.

Therefore, rework is a source of waste in product development projects and waste must be eliminated in order to deliver the project on time, on budget and using minimal resources. The presence of rework in product development projects indicates that the project performance can be improved if this source of waste is eliminated.

Table 1.5

Topics that influence project performance

Topic	Authors
Objective misalignment between the strategic and operational organization levels	(Payette, 2016)
Product development project categories	(Shenhar et al., 2016)
Organizational project portfolio balance	(Archer & Ghasemzadeh, 1999)
Incorrect estimates during the planning phase	(Kerzner, 2011; Samset & Volden, 2016)
Lack of management acquaintance among technical functional managers	(de Brentani & Kleinschmidt, 2015; Lechler & Thomas, 2015; Petro & Gardiner, 2015)
Scarce and super allocated resources, meaning unbalanced resource allocation to projects	(Browning & Yassine, 2016; Hoppmann, Rebentisch, Dombrowski, & Zahn, 2015; Padovani & Carvalho, 2016)
Nonconvergent rationales between management and engineering departments	(Gaynor, 2015; Marion & Meyer, 2011)
Insufficient knowledge and uncertainty related to the product development and development process	(Bhuiyan & Thomson, 2015; J. F. Maier, Wynn, Biedermann, Lindemann, & Clarkson, 2014)
Lack of involvement and knowledge sharing between suppliers and customers	(Lawson, Krause, & Potter, 2015; Sariola & Martinsuo, 2016),
Miscommunication and misinterpretation due to geographic dispersion and different cultures, languages and time zones	(Gaynor, 2015; Yang, Kherbachi, Hong, & Shan, 2015)
Lack of coordination in exchanging information between interdependent processes	(Parraguez, Eppinger, & Maier, 2016)
Changes in goals and specifications not well communicated	(Shenhar et al., 2016)
Rework and non-value added activities throughout the project life cycle	(Browning & Yassine, 2016; Eres, Bertoni, Kossmann, & Scanlan, 2014; Lessard, Sakhrani, & Miller, 2014; Oppenheim, 2011, p. 16)

(Melo, 2019)

1.3 ENGINEERING DESIGN REWORK

This section introduces the definition of engineering design rework in product development projects as well as the justification for choosing the engineering design process as the environment where rework occurs. A discussion of some effects of engineering design rework that negatively impact the product development project performance follows. Finally, the process undertaken to validate the managerial problem with practitioners is described.

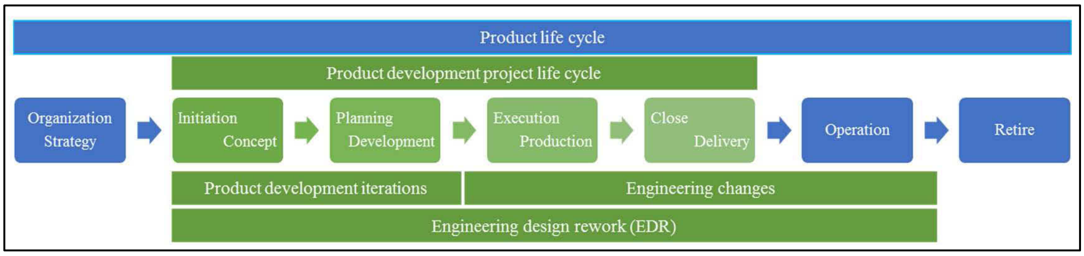
1.3.1 Engineering design rework definition

Rework can be defined as the action of redoing an activity because of the identification of a problem (Love, 2002). This study investigates **engineering design rework (EDR)**, i.e., rework activities related to the product design defined by the development engineering team throughout the engineering process in a product development project.

Some authors consider the EDR that happens *before* the engineering design freeze as normal iterations of the product development project. The engineering design freeze in a project life cycle is generally the transition between the planning and execution phases. Therefore, the EDR that occurs *after* the engineering design freeze is called "engineering change" (Jarratt et al., 2010), as illustrated in Figure 1.3.

Figure 1.3

Engineering design rework



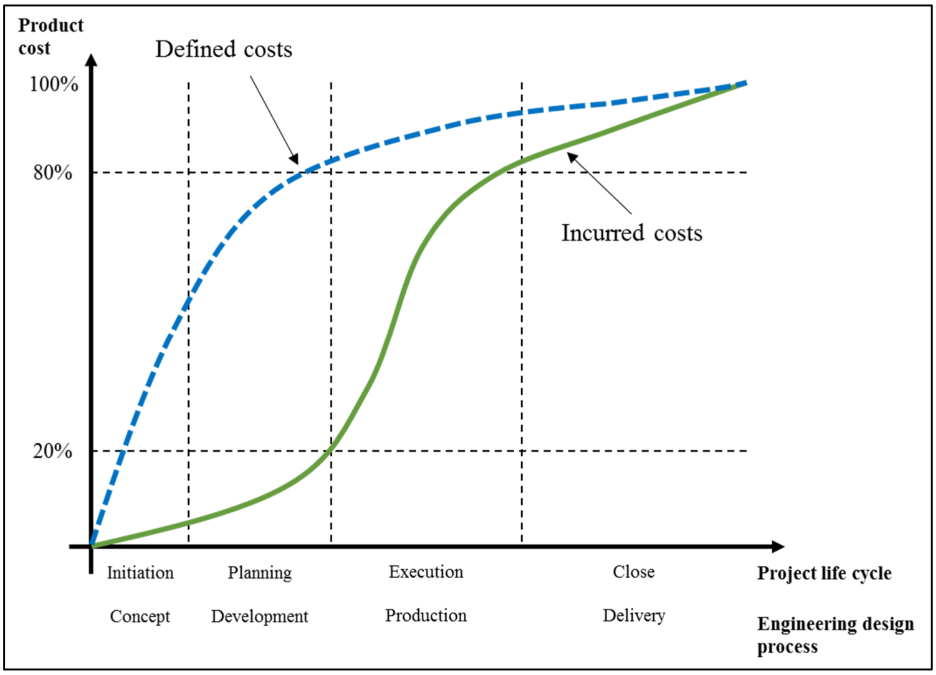
(Melo, 2019)

Engineering change is referred to by synonyms such as redesign (Jagtap & Johnson, 2010), design change (Hamraz, Caldwell, & Clarkson, 2013), product change, product design change, engineering design change, and engineering change (Jarratt et al., 2010). As defined by Hamraz et al. (2013), engineering changes are any modification in technical drawing and documentation, bill of materials, software, definition of product fit, form and function after the official release of a design by the engineering design team.

There are two principal reasons to justify this research on EDR. The first is based on the fact that 70 % to 80 % of product costs are defined by the design (K. Clark & Fujimoto, 1991; Kovacic & Filzmoser, 2014; Stark, 2005). Thus, careful attention should be paid to the preliminary phases of the design engineering process, when the most important decisions for a project are made, but the meaningful amount of costs has not yet been incurred (Anderson, 2014). Figure 1.4 depicts the defined costs and incurred costs idea throughout the project life cycle.

Figure 1.4

Product development projects: defined versus incurred costs



(Melo, 2019) adapted from (Anderson, 2014; Karniel & Reich, 2011)

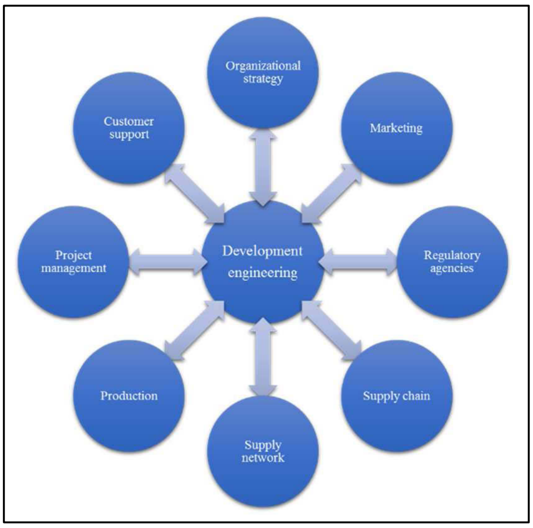
The second reason is that the development engineering team is the core of a product development project, meaning that the other project teams rely on the data, information and knowledge generated by the development engineering team. Thus, if the development engineering team generates improper, incorrect, low-quality, erroneous or inappropriate design definitions, these issues are likely to impact their own activities as well as the activities of the upstream and downstream teams involved in the product development project.

For instance, upstream teams depend on the development engineering team to perform estimates (Hoppmann et al., 2015) and technical-commercial feasibility analysis (Albers, Gladysz, Heitger, & Wilmsen, 2016; Ulrich & Eppinger, 2012). In the case of downstream teams, such as supply chain, their activities are based on decisions made previously by development engineering teams (Han, Lee, & Nyamsuren, 2014).

Figure 1.5 represents the development engineering team at the center and the other teams, such as marketing, regulatory agencies, the supply chain, the supply network, production, project management, customer support and organizational strategy interacting with the development engineering team.

Figure 1.5

Development engineering team as the core of a product development project



(Melo, 2019)

Although the importance of the engineering design process in relation to the overall product development project performance has been recognized, previous studies have shown that EDR can consume up to 50 % of a development engineering team's daily activities (Graham, 1999; Hamraz & Clarkson, 2015). In other words, development engineering teams potentially spend up to half of their capacity on rework.

1.3.2 EDR effects on product development project performance

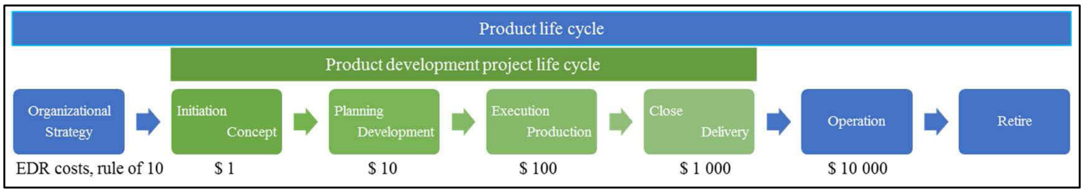
To illustrate how engineering design rework may jeopardize product development project performance, some effects of EDR on product development project performance are discussed below. These effects include EDR impact on the project cost, EDR knock-on effects, EDR impact on the project schedule, the change and configuration management processes in relation to EDR, and team frustration related to EDR.

1.3.2.1 EDR impact on the project cost

The EDR cost depends on the stage of the product life cycle in which the engineering problem was detected, and it is expected to increase at each step as the product development project progresses further. The progressive increase in the EDR cost is explained by the "rule of ten", meaning that the cost increases approximately ten times for each phase in the product life cycle during which the problem continues to go unnoticed (Fricke et al., 2000; Hamraz et al., 2013; Jarratt et al., 2010), as illustrated in Figure 1.6.

Figure 1.6

EDR costs based on the "rule of ten" in the product development project



(Melo, 2019)

For example, if an engineering definition problem in the drawings or the bill of materials is identified while a project is still in the planning phase or before the design is released to the execution phase, the EDR cost is lower than if the problem is found in the execution phase, when the team has been working with incorrect information. Thus, the EDR cost would be higher if, for example, the procurement team had already bought materials based on the bill of materials or if the production team had already manufactured or assembled parts based on the drawings (Eger, Eckert, & Clarkson, 2005).

A report from the Automotive Industry Action Group (2012) registered 350,000 engineering changes of which some could have cost approximately $ 50,000 (Hamraz & Clarkson, 2015; Wickel & Lindemann, 2015). A survey of European and United States of America (USA) organizations indicated that an average of 330 engineering changes per month were executed, with each change costing approximately $ 1400 (Joshi, Ameri, & Dutta, 2005). This result is consistent with the Aberdeen Group's report that classified the cost of changes depending on product complexity, with costs ranging from $ 1492 to $ 5886 for low to high complexity (Quintana, 2011).

1.3.2.2 EDR knock-on effects

EDR knock-on effects, also called the snowball effect or change propagation, contribute to the "rule of ten" in increasing the cost. They emerge from the impacts generated by EDR due to the high level of interdependency between product's parts (Hamraz & Clarkson, 2015). The impacts affect not only the product design definition but also software, documents, toolings and project team activities (Jarratt et al., 2010). Each affected element may trigger other rework throughout the product life cycle (Hamraz & Clarkson, 2015). In the worst-case scenario, when the knock-on effects are catastrophic, they are characterized as the avalanche effect (Hamraz & Clarkson, 2015).

The Aberdeen Group study concluded that EDR may result in "scrap, wasted inventory, and disruption to supply and manufacturing" (Jarratt et al., 2010) in addition to affecting human and material resource plans, production plans, production tooling and aftermarket customer support (Hamraz et al., 2013).

A study mentioned by Jarratt et al. (2010) found that approximately 88 % of the participating organizations were unable to correctly identify EDR impacts along a product life cycle. That is why, for over a decade, authors have been trying to develop methods and tools to predict EDR impacts, also known as engineering change propagation (Clarkson, Simons, & Eckert, 2004; Earl, Eckert, & Clarkson, 2005; Eckert, Clarkson, & Zanker, 2004; Eger et al., 2005; Hamraz et al., 2013; Hamraz & Clarkson, 2015; Jarratt et al., 2010; J. F. Maier et al., 2014).

These methods and tools are intended to help designers make better decisions when EDR needs to be implemented. They allow the assessment of different propagation paths from alternative solutions of the identified problem. The decision trade-off is assessed depending on the project priorities, such as cost, time, quality standards and safety aspects (Eckert et al., 2004).

The prediction of EDR impacts involves several parameters and information about the product, project plans, human resources, information systems, product components and logistics. During 10 years of research, authors have studied methods and tool prototypes for evaluating products with different levels of complexity, ranging from helicopters to hair dryers and vacuum cleaners (Clarkson et al., 2004; J. F. Maier et al., 2014).

1.3.2.3 EDR impact on the project schedule

Once EDR is deemed to be required, and the EDR impacts are identified, it may be necessary to replan the project schedule. However, to update the schedule, it is necessary to estimate the overall work effort, resource availability and implementation duration.

The estimate of the EDR work effort includes the estimation of the EDR propagation effect in the product life cycle. However, it also depends on the project progress. The EDR work effort can range, for example, from a graphical drawing correction to an entire system redesign. As mentioned in previous studies (Jarratt et al., 2010; Riviere, 2003; Wu, Fang, Wang, Yu, & Kao, 2014), it can be a type of mini-design.

After assessing the EDR work effort, it is necessary to assess the resource availability. The affected resources can range from one person to many teams, in addition to scarce resources such as experts, equipment and laboratories. As described by Earl et al. (2005), the resources required for EDR can be of two types: the same team that is working on the product development or a dedicated team to work on the EDR.

In the case of using the same team, product development and EDR activities will be executed concurrently; thus, activities will compete for resources (Hamraz et al., 2013), and prioritizing and reordering planned activities may be necessary (J. F. Maier et al., 2014). Otherwise, time pressure in the work environment can lead to bad decisions during product development and the consequent increase of additional EDR in the future, as suggested in a study by Dostaler (2010). On the other hand, if the organization has a dedicated team that is responsible for EDR, a period for learning about the problem should be allocated. The amount of time will depend on the availability of the original design engineer and the available information (Earl et al., 2005).

The duration of EDR, including its impacts, depends on the previous assessment of the work effort and resource availability. The duration can range from days to months to years of work (Jarratt et al., 2010). This assessment is necessary to provide a realistic forecast for the project, enabling project managers to efficaciously address the project challenges.

Overall, it is important to consider that in a product development project, several instances of EDR are expected, but they are not all planned. Indeed, if there is no replanning, product development can enter a vicious loop that may strangle the product development (Graham, 1999).

Some authors (Jarratt et al., 2010; Riviere, 2003; Wu et al., 2014) consider EDR a mini-product development process that occurs concurrently with the product development project (Hamraz et al., 2013; Kusiak, Wang, He, & Chang-Xue, 1995). Indeed, Fricke et al. (2000) consider product development a continuous change management process. This conclusion is supported by a survey of German organizations (Fricke et al., 2000) and a study of 90 Danish engineering organizations (A. Maier & Langer, 2011), which found that almost 30 % of daily engineering activities included rework activities. Another study found that the amount of rework in engineering activities is even larger, between 33 % and 50 % (Hamraz & Clarkson, 2015; Loch & Terwiesch, 1999).

This significant amount of EDR in engineers' routine may end up strangling the planned product development. Then EDR occurs, instead of focusing on the priorities at hand and the planned design activities, engineers need to split their attention between the on-going development effort, supporting the supply chain (Brandao & Wynn, 2009), and the rework effort. In a United Kingdom survey, more than 50 % of the participating organizations considered "engineering changes as a major source of problems in their product development process" (Jarratt et al., 2010).

1.3.2.4 Change management, configuration management and EDR

Engineering change management and configuration management are processes impacted by EDR that occurs during product development projects. The engineering change management process ensures change implementation throughout the affected supply chain (Hamraz et al., 2013). The configuration management process ensures the traceability of the product throughout the product life cycle, tracking the applied changes and all product information (Riviere, 2003).

Wynn and Eckert (2016) observed that the configuration management process often starts before the completion of the “design phase”. However, the change management process is initiated after the release of the engineering design, meaning that EDR that occur before the engineering design release are not tracked because they are considered normal iterations of the product development.

An additional challenge is that tracked EDRs are not the totality of EDRs that happen in the project, and even though the engineering change and configuration management processes are of great importance in managing the project, they are extremely bureaucratic processes that contribute to reducing the project progress pace.

However, not tracking EDR, including product development iterations, prevents an organization from acknowledging EDR existence, measuring EDR associated cost, realistically updating the project plan, learning from previous mistakes, assuring product traceability, performing technical validation to reduce knowledge gaps and assessing potential negative impacts on product performance.

1.3.2.5 Team frustration

In addition, EDR and its associated effects are a source of frustration to the team involved in the project. For example, on the Boeing 787 project, thousands of technicians and engineers dedicated much time, and in the end, they did not feel satisfied with the project results (Gaynor, 2015). Design teams become frustrated when they need to revise their earlier decisions due to a problem discovered afterwards (Kennedy, Sobek, & Kennedy, 2014), especially if this happens often.

1.3.3 Managerial problem validation

As part of the requirements of the preliminary phases of the DBA program, the student must validate whether the chosen managerial problem is relevant for study, whether it is correctly stated and whether it is a real challenge for organizations. This validation process precedes the research methodology definition, which includes the data collection and data analysis strategy definition. Moreover, this validation is intended to contribute to the research perimeter and scope definition.

The validation of the managerial problem of this research comprised the following steps: preparing the semistructured interview questions, identifying practitioners with experience in managing product development projects in the aviation industry, conducting the interviews with practitioners and analyzing the interview results. This process took approximately four months.

Seven telephone calls and face-to-face semistructured interviews were performed. The interviewees' product development projects included the development of jet aircrafts, helicopters, structural parts and systems. The hierarchical level of the interviewees included senior engineers, managers, directors and vice presidents. In addition, the 7 participants were of different nationalities and located in different countries. Table 1.6 summarizes the interviewee information.

In general, EDR is understood by practitioners as a quality fault in the design engineering process; this understanding is supported by the literature (K. G. Cooper, 1980; Lieberman, 2012; Yassine, Whitney, & Zambito, 2001). Additionally, practitioners consider EDR an intrinsic technical risk associated with product development, depending on the level of uncertainty and available knowledge; this idea is also supported by the literature (Shenhar et al., 2016; Unger & Eppinger, 2011; Weil & Dalton, 1992).

Table 1.6

Residence enterprise semistructured interviewee information

Project product	Interviewee role and hierarchy level	Interviewee nationality	Organization/Country
Jet aircraft	Engineering project management manager	Brazil	OEM/Brazil
Jet aircraft	Strategy & business development manager	Mexico	OEM/Canada
Jet aircraft	Retired – Senior engineer	USA	OEM/USA
Helicopter	Product policy upgrades	Brazil	OEM/France
Helicopter	General operations manager	Brazil	OEM/Ireland
Structural parts & System	Director	Canada	Supplier /Canada
Structural parts & System	Vice President of design and development	Brazil	Supplier/Canada

(Melo, 2019)

Two approaches to addressing EDR were mentioned by the interviewees during the managerial problem validation process. The first is the reactive approach, in which EDR will be performed when the need for correction is discovered (Dostaler, 2010; Sterman, 1992). The second is the proactive approach, with quality gates throughout the engineering design process, to reduce the fault discovery time (Akkermans & van Oorschot, 2016; Love et al., 2008).

The validation process confirmed that the **managerial problem of interest of this study, which is the presence of EDR in product development projects**, is a recognized managerial problem that must be investigated to improve project performance. The interviewees recognized that they do not know how to anticipate the likelihood of EDR because it is embedded in the engineering design process.

Usually, organizations have lagging indicators for EDR, that measure the problem after the fact, for instance, the amount of revised drawings and the tracking of major design change life cycle milestones. However, organizations lack leading indicators for EDR because such indicators can support decision making during product development to avoid and mitigate rework. The use of lagging indicators rather than leading indicators was observed in the validation process interviews, as well as in the literature (Love et al., 2018; Williams, Jonny Klakegg, Walker, Andersen, & Morten Magnussen, 2012).

During one interview conducted throughout the managerial problem validation process, the interviewee recognized that the engineering design rework challenge is very relevant to his organization, especially in the preliminary phase of product development projects. This realization allowed the researcher to perform an internship over 1.5 years with 20 hours per week onsite access to data and key product development stakeholders.

Before the validation process, the managerial problem was being studied as a process-based view of a product development project in isolation. However, throughout the validation process, interviews as well as the internship opportunity brought to light other aspects of the overall project context, such as the highly dynamic changing environment and managerial decisions during the product development project influenced EDR and project performance. Further analysis of this topic is discussed in chapter 2 and supported by an extensive literature review.

1.4 MANAGERIAL PROBLEM SUMMARY

Even though projects are recognized as a way for organizations to achieve their strategic objectives (Meredith & Mantel, 2011, p. 90; Milosevic, 2006), project performance results can be significantly improved. For instance, the survey prepared by the PMI of 4455 project management practitioners showed that only 57 % of projects were on budget, and only 52 % were on time (PMI, 2018). Specifically, in terms of product development projects, the success rate remains arguably modest at approximately 60 % (Kalluri & Kodali, 2014). Thus, improving project performance can contribute to the achievement of organizational strategic objectives.

Three game-changing product development projects were presented to illustrate the challenges faced by complex product development projects. It was observed that the three projects overran their multibillion-dollar budgets by more than 50 % and needed at least 40 % extra time to complete the project. The poor performance of those projects was influenced by technical and managerial problems, as summarized in Table 1.4.

Williams (2005) affirms that the compound of complexity, uncertainty and tight time constraints are the fundamental factors for the poor performance of projects. Wysocki (2011) adds *change* due to the dynamic project environment as a contributing factor. These four factors were observed in the three game-changing product development projects presented.

Some topics being investigated in consulted literature that negatively influence project performance are listed in Table 1.5. Among them, rework is the primary topic of interest in this research, specifically **engineering design rework (EDR),** meaning rework activities related to the product design defined by the development engineering team throughout the engineering process in a product development project.

Two main reasons justify this choice. First, approximately 75 % of product costs are defined by the design (K. Clark & Fujimoto, 1991; Kovacic & Filzmoser, 2014; Stark, 2005). Second, project teams rely on the data, information and knowledge generated by the development engineering team (Albers et al., 2016; Han et al., 2014; Hoppmann et al., 2015; Ulrich & Eppinger, 2012).

In spite of the importance of the engineering design process to the entire product development project performance, previous studies have shown that EDR can represent up to 50 % of the development engineering team’s daily activities (Graham, 1999; Hamraz & Clarkson, 2015) in addition to the numerous EDR effects on the product development project performance.

Finally, the **managerial problem, which is the presence of EDR in product development projects,** was validated and recognized by seven practitioners in the aviation industry as a significant managerial problem that needs to be investigated in order to improve future project performance. The practitioners consulted agreed that they could not anticipate the occurrence of EDR. They highlighted two main approaches to dealing with EDR: the reactive approach – execute rework as it is discovered – and the proactive approach – execute quality gates throughout the engineering design process.

CHAPTER 2 - THEORETICAL CONTEXT

The objective of this chapter is to map and assess the relevant scientific documents that contributed to the understanding of the EDR phenomenon in product development projects. To achieve this objective a literature review process was performed that included the selection and analysis of documentation followed by the identification of four emerging themes and three research streams. By positioning this research against the available literature, the last part of the chapter presents the theoretical framework, the research questions and the gap in the literature covered by this research.

2.1 RESEARCH LOCATION ANALYSIS

The literature review process comprises two main parts. The first part concerns the document selection, and the second concerns an in-depth analysis of the documents selected. The results of the in-depth analysis were organized into three main categories according to their literature domain: construction literature, product development literature and project literature.

2.1.1 Documents selection for the literature review

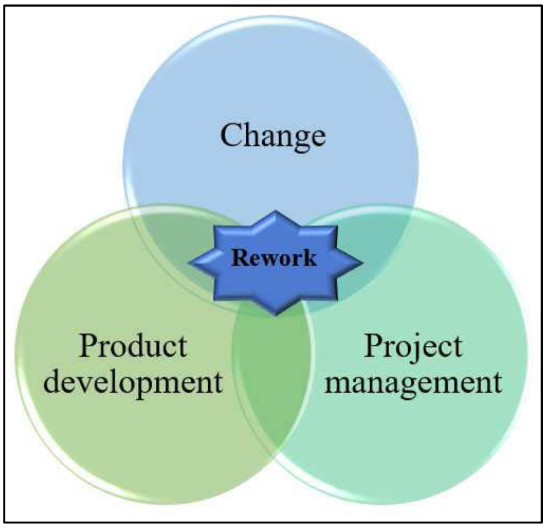
According to Tranfield, Denyer, and Smart (2003), a literature review is a process to map and assess the existing knowledge concerning an academic inquiry. Thus, to position this study in relation to the existing studies, a systematic literature review was performed following a sequence of steps adapted from the processes performed in (Geraldi, Maylor, & Williams, 2011; Khan, Kunz, Kleijnen, & Antes, 2017; Morioka, Bolis, & Carvalho, 2018).

Step one concerns the selection of the documents to be analyzed. The search was performed on the Web of Science and Scopus databases, as they include peer-reviewed studies published in indexed journals (Carvalho, Fleury, & Lopes, 2013). The Google

Scholar search engine was also used to identify other documents not included in the aforementioned databases (Lunny, Brennan, McDonald, & McKenzie, 2017).

The meaningful keywords for the present literature review were “rework”, “project management”, “product development” and “change”. Thus, the resulting search string was “(rework AND (project management OR product development OR change))”, meaning that the search was looking for documents containing the keywords rework and project management, rework and product development, or rework and change. Figure 2.1 presents the idea in a Venn diagram, which defines the limits of this literature review.

Figure 2.1
Literature review perimeter



(Melo, 2019)

In the Web of Science and Scopus databases, the search results should present the aforementioned keywords in the title, abstract or keyword search fields. The search results were limited to articles and reviews, excluding proceedings papers. In the search engine Google Scholar, the search results were sorted by the relevance of the documents, patents were excluded, citations were included and the search was not limited to any time period. The searches for this literature review were last updated on July 2019.

The search on the Web of Science database found 266 documents, the search on the Scopus database found 502 documents and the search on Google Scholar found over 1000 results.

Step two concerns the refinement of the document sample identified in step one. Documents were prioritized by relevance and by publication date. The selection of documents was based on the assessment of each document's title and abstract. Documents not concerning rework and project performance as well as documents in which full text was not available were excluded from the document sample.

Thus, after the assessment of the titles and abstracts of the documents, the sample size was reduced to 115 documents.

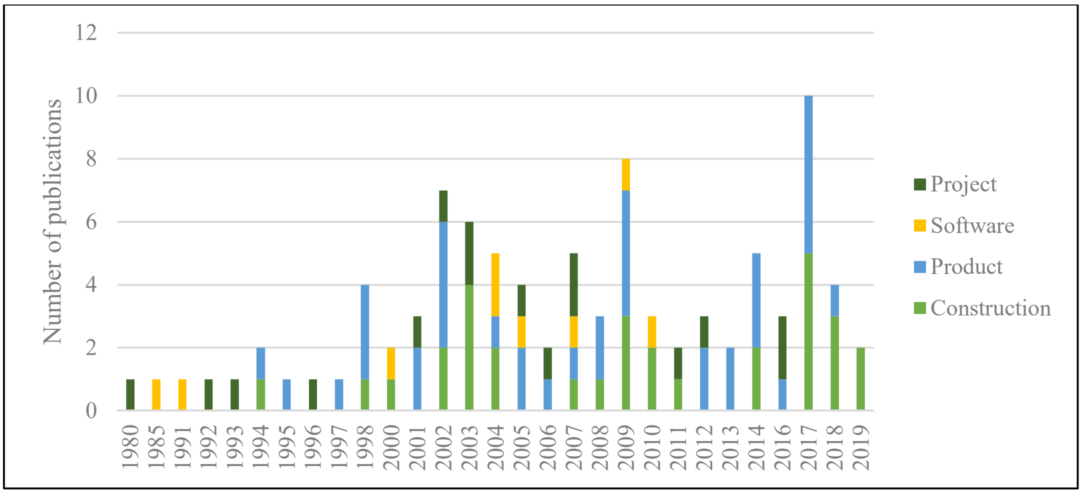
Step three concerns performing a narrow refinement of the body of knowledge for this literature review. The exclusion criteria for this step were documents that did not investigate rework related to engineering and/or the design environment, for example, studies that were interested in understanding rework in the manufacturing or production environments and in which the rework was not driven by design. After assessing the remaining documents and achieving information saturation, the sample size was reduced to 93 documents.

The publication dates of the 93 documents ranged between 1980 and 2019. The main areas of interest of the studies were product, software and construction projects. Thus, the documents assessed were classified by industry based on product, software, construction, or project; the last category concerned publications that did not fit in the previous categories.

Figure 2.2 presents the distribution of the document sample publications each year by category. The data show that the software development literature has contributed with publication on rework since 1985; however, it was not consistent. On the other hand, studies on rework have appeared in the construction and product literature since 1994, and scholars in these fields are the major contributors to studying the topic. In addition, as shown by the data presented in the graph, the construction literature presented more recent publications than the product development industry in the last three years.

Figure 2.2

Distribution of the publication sample of 93 documents each year by category

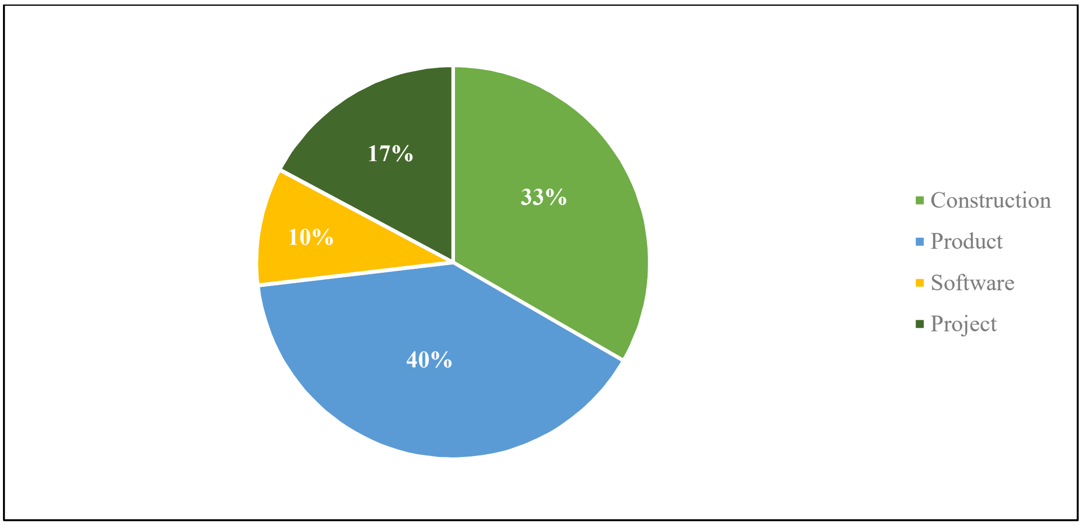


(Melo, 2019)

Figure 2.3 shows that 40 % of the publications relate to product development projects, 33 % relate to construction projects, 10 % relate to software and the remaining 17 % relate to project aspects not specific to any industry.

Figure 2.3

Distribution of the publication sample of 93 documents by industry



(Melo, 2019)

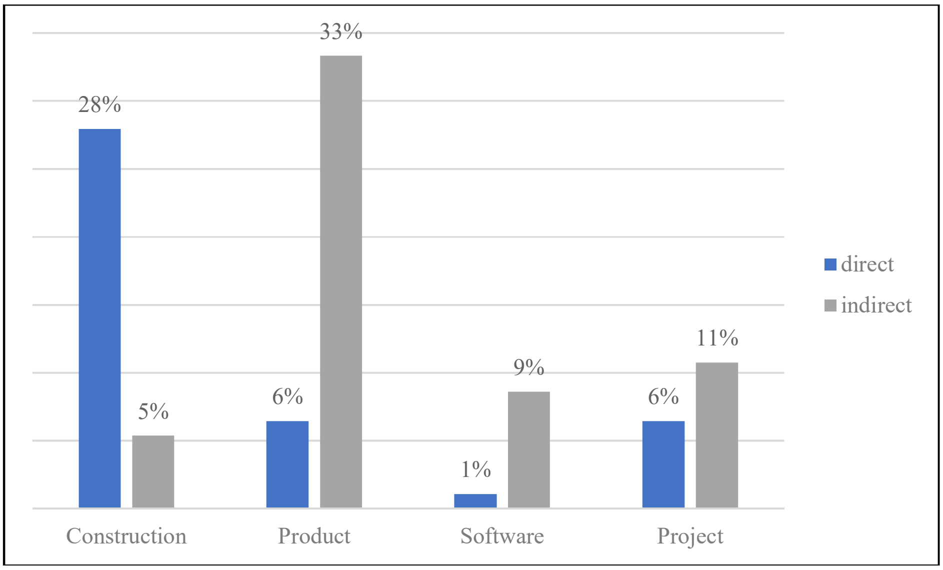
The documents were classified as "direct" and "indirect" depending on whether the rework was the main subject or a peripherical topic of the study. Considering this classification, Figure 2.4 shows that the construction literature accounts for 28 % of the publications that investigate rework as the main subject compared to only 7 % of the product and software development literature combined. The construction literature investigates rework as the main topic almost four times more often than the product and software development literature. On the other hand, 42 % of the product and software development literature considers rework as a peripherical topic. This suggests that the presence of rework is recognized in product development projects, but there is still a gap in the product development literature in terms of investigating rework.

The list of the document sample sources is presented in annex A, and the information was organized on the basis of each category suggested previously.

Step four concerns the in-depth analysis of the sample of 93 documents selected in the previous step. The results of this step are discussed as follows.

Figure 2.4

Publication sample of 93 documents as direct or indirect in addressing rework



(Melo, 2019)

2.1.2 Document sample analysis for the literature review

The content of the document sample was analyzed based on the perimeter, including rework and change domain, rework and project management domain and rework and product development domain, as previously presented in Figure 2.1. The findings of the analysis are presented in the sequence and are organized into three subsections: construction literature, product development literature, and project management literature.

2.1.2.1 Construction literature

The construction literature brought to light several aspects for better understanding rework and its relationship to project management. The construction industry recognizes rework as a problem within its projects, and studies have appeared since the early 1990s (Ledbetter, 1994), particularly the many contributions of Professor Peter Love (Love et al., 2010; Love, Mandal, et al., 1999; Love, Smith, et al., 2019). As presented in Figure 2.4, among the 93 documents found in step four of the literature review process, 28 % of the studies that directly investigate rework are from the construction literature.

Sommerville (2007) observed that the terminology for rework presents high level of ambiguity. The author also identified confusion in the literature associated with the definition of rework and defects, quality deviations, nonconformance, quality failures, errors and omissions. As stated by the author in order to truly understand, measure, prevent and correct rework, an initial challenge is to define the rework concept and establish its perimeter.

The construction literature provides evidences of the confusion regarding the causal relationship between rework and change. According to Sun and Meng (2009), rework is a natural consequence of a change, and according to Love, Holt, Shen, Li, and Irani (2002), changes may be triggered by reworking activities in the project. The causal relationship between change and rework seems to be cyclical or bidirectional.

The causes of rework in the construction industry have been investigated for more than 20 years, mainly in the research undertaken by Professor Peter Love (Love & Edwards, 2004; Love, Edwards, Irani, & Forcada, 2014; Love, Edwards, Smith, & Walker, 2009; Love, Li, & Mandal, 1999; Love & Smith, 2003) and in recent studies such as Eze (2018) and Safapour and Kermanshachi (2019).

Authors (Hwang, Thomas, Haas, & Caldas, 2009; Love et al., 2010; Love & Irani, 2003; Love & Li, 2000) investigated the causes and costs of rework in construction projects and observed a lack of concern about quality in the construction industry. This finding is aligned with Ledbetter (1994), who considered project rework costs as part of the quality costs related to deviation corrections. Authors (Hwang et al., 2009; Hwang, Zhao, & Goh, 2014; Love et al., 2010; Love & Irani, 2003; Love & Li, 2000) also related rework costs to quality costs.

Among the rework causes in the construction industry, those related to design change were given special attention in recent studies (Wilson & Odesola, 2017; Yap, Abdul-Rahman, Wang, & Skitmore, 2018; Yap, Low, & Wang, 2017; Yap & Skitmore, 2017). Some studies (Hwang et al., 2014; Love, Ika, Ahiaga-Dagbui, Locatelli, & Sing, 2019) investigated rework due to changes initiated by customers. Sommerville (2007) sought to better understand the rework phenomenon in new home building projects and its causes considering product quality and customer requirements.

To minimize the overall impact of changes on project performance, i.e., cost and delay, researchers are developing tools and methods to predict the change impact propagation in a project. These studies seek to provide methods and tools for professionals to increase their capacity to make better decisions. For example, in the construction industry, Zhao, Lv, Zuo, and Zillante (2010) proposed a change prediction system to facilitate change management. The changes can be predicted by setting the change criteria for each project activity in the form of rework scope. Park and Peña-Mora (2003) developed a dynamic change management model to help managers decide between reworking activities in the project construction phase or changing the design specifications that were previously released for that phase.

Alarcón and Mardones (1998) investigated the impact of communication and activities sequencing on the performance of construction projects. They observed that little interaction between the design and construction teams in building projects as well as the work sequence may result in change orders, rework, and project delays. The authors found that improvements to construction project performance could be obtained from improving the work sequence and the overall design and construction interface.

Based mostly on a retrospective analysis of construction projects, some studies (Love, 2002; Love, Irani, & Edwards, 2004; Love & Li, 2000) evaluate facets such as the relationship of the rework to the type of project or the procurement methods.

2.1.2.2 Product development literature

The product development literature recognizes the presence of rework in projects. However, as presented in Figure 2.4, rework has not been investigated as a central topic in the product development literature. Among the 93 documents found in step four of the literature review process, only 7 % of the documents of the product development literature, including software development, investigate rework as a central topic compared to 42 % that indirectly consider rework.

In the researcher's understanding, rework is a peripheral topic in the product development literature because it is generally assumed to be part of a product development project. Although rework may be necessary to adjust the product being developed, and some authors describe rework as a necessary evil within a product development project, it is a disruption to the development process (Kennedy et al., 2014; Sosa, 2014).

Based on the literature reviewed, the main focus of the product development studies has been proposing solutions to reduce the development cycle; however, these solutions are associated with the risk of creating rework. From this perspective, rework is a consequence of the strategies investigated to reduce the product development cycle, which may explain why rework is recognized in the product development literature but is not investigated as the main object.

To reduce the product development cycle and develop better products, Eppinger, Whitney, Smith, and Gebala (1994) proposed a model-based method to organize task sequencing in product development. The authors used the design structure matrix to better understand the technical interdependencies between activities and to be able to propose a consequent optimized activity sequencing. Karniel and Reich (2009) presented a literature review of DSM-based models for design process simulation.

In software development projects, the importance of activities sequencing to improve quality and productivity was recognized in the mid-1980s (Radice, Roth, O'Hara, & Ciarfella, 1985). In addition, some studies (Antoniol, Lucca, & Penta, 2004; Hanne & Nickel, 2005) proposed simulation models to define activities sequencing that included the possibility of rework.

Simulation models that seek to reduce the product development cycle by overlapping sequential activities were proposed (Akkermans & van Oorschot, 2016; Browning & Eppinger, 2002; Krishnan, Eppinger, & Whitney, 1995, 1997; Lin, Chai, Brombacher, & Wong, 2009; Lin, Chai, Wong, & Brombacher, 2008; Lin, Qian, & Cui, 2012; Loch & Terwiesch, 1998; Terwiesch, Loch, & Meyer, 2002; Yang, Zhang, & Yao, 2012; Yassine, 2007; Yassine, Sreenivas, & Zhu, 2008; Yassine et al., 2001). However, the authors recognized the risk that this approach, depending on the level of overlap between activities, could necessitate rework.

In the same direction, J. F. Maier et al. (2014) developed a simulation model to prioritize design activities in product development projects considering the combined effects of progressive iteration, rework and change propagation. Additionally, Lévárdy and Browning (2009) proposed an adaptive product development process rather than a predefined single optimal product development process.

Among the possible causes of rework identified in the simulation models that seek to reduce the development cycle, Krishnan et al. (1997) considered the rework risks in relation to the upstream information evolution and the downstream teams' iteration sensitivity. Terwiesch et al. (2002) considered the precision and stability of preliminary information, and Yassine, Maddah, and Nehme (2013) considered whether preliminary information should be used by downstream activities as a function of the information quality. Yassine (2007) considered the rework probability based on the duration variance of development processes and the process robustness in terms of being impacted or not impacted by changes. Lin et al. (2008) and Woschke et al. (2016) considered development errors and input information changes.

Some authors (Ahmad, Wynn, & Clarkson, 2013; Ullah, Tang, Wang, & Yin, 2017a; Ullah, Tang, Wang, Yin, & Hussain, 2017; L. Yin et al., 2017) proposed simulation models to support the assessment of engineering change impacts on product development in order to manage the implementation of such changes and to mitigate the project disruption of implementing them. Giffin et al. (2009) proposed a change propagation analysis by creating indices to measure the behavior of the product system in accepting, repelling or propagating changes, which is similar to the sensitivity constructs discussed by Krishnan et al. (1997).

Studies investigated requirement changes and their impact on product development projects due to the need of rework (Tan, Otto, & Wood, 2017; Ullah, Tang, Wang, & Yin, 2017b; White, Iammartino, & Fossaceca, 2018). L. L. R. Rodrigues, Dharmaraj, and Shrinivasa Rao (2006) developed a model to better understand product development project dynamics when scope change occurs due to the development of new technology.

Additionally, authors of software development studies proposed frameworks and models to predict change due to input changes. Chua and Verner (2010) proposed a framework to better estimate the cost of the necessary rework that needs to be undertaken due to requirement changes in software maintenance, i.e., after software delivery. Ferreira, Collofello, Shunk, and Mackulak (2009) developed a system dynamics simulation model to help professionals understand the complex impacts related to requirements volatility on software development projects.

Loch and Terwiesch (1998) developed a simulation model to assess the influence of communication to mitigate rework when overlapping activities to reduce the development cycle. Ragatz, Handfield, and Petersen (2002) discussed the benefits to the project performance associated with integrating the supplier into the product design under conditions of technology uncertainty. Nambisan (2002) studied designing virtual customer environments for product development and found that customer involvement during product testing helped minimize costly redesign and rework.

A relationship between project quality and rework has also been observed in software projects; for example, Harter, Krishnan, and Slaughter (2000) found that higher levels of process maturity in software development projects are associated with higher product quality. Higher product quality leads to fewer product defects and thus to less rework and a reduced development cycle and development effort.

Thus, the studies on rework in the product development literature generally seek solutions to reduce the product development cycle so that organizations can deliver products to the market more quickly. Here lies a paradox because the solution commonly identified in the literature to reduce the development cycle is overlapping sequential activities, but because of the complex environment of product development projects, this alternative may result in an amount of rework that may undermine the initial goal of reducing the development cycle. Therefore, rework is not the investigative core of the studies assessed in this section but is considered a risk, and the studies estimate the probability and impact of rework to minimize its effects on the project performance.

2.1.2.3 Project management literature

Consulting professionals and management scholars have acquired meaningful experiential learning from postmortem project analysis. Their objective has been to identify the causes of project cost overruns and delays in litigation processes and the portion of customer liability. To achieve this objective, they have used management science modeling techniques to model and analyze complex projects (Cicmil, Williams, Thomas, & Hodgson, 2006), for instance, large-scale projects in engineering, software and construction. Some authors believed that improved project performance can be achieved by better understanding the project dynamics, including activities sequencing and the interactions among the project objectives, scope and resources (Ford & Sterman, 1998; Godlewski et al., 2012; Sterman, 1992).

Ford and Sterman (1998) proposed a system dynamics model of a product development process that considered development activities, dynamic concurrence and iteration. Ford and Sterman (2003a) investigated product development planning and the influence of hiding the need for rework as well as management decisions that neglect long-term effects.

Ford and Sterman (2003b) highlighted the rework effect, personifying it as the "90 % syndrome", which suggests that some projects are perceived as having achieved 90 % completion of the planned activities; however, due to the need for rework, the project seems to stagnate, and in the end, the project takes double the planned time to achieve completion. The 90 % syndrome is in alignment with the firefighting concept in product development presented by Black and Repenning (2001).

Iteration is a common phenomenon in large and complex projects. Its presence is recognized in product development, software development and construction projects, and it is considered a meaningful contributor to cost and schedule overruns in projects. In their literature review, Wynn and Eckert (2016) proposed a taxonomy for iteration in which rework is considered a synonym. The study highlighted the plurality of perspectives concerning the phenomenon, including the causes, effects and types. Last, the study revealed that even though the presence of rework in such projects is undeniable, there is a gap in traditional project management in terms of measuring and anticipating the rework.

A major discovery of postmortem project analysis is the archetypal structure of the rework cycle (Owens, Leveson, & Hoffman, 2011). The rework cycle goes beyond the intuitive traditional project planning and control. First, it assumes that activities are not performed perfectly, so that a certain amount of imperfection may require rework. In addition, studies about the rework cycle investigated concepts such as real and perceived project progress, variable professional productive level and the discovery time needed to identify imperfection. All those factors affect the project performance (K. G. Cooper, 1980, 1993a; A. Rodrigues & Bowers, 1996).

Few studies (Forcada et al., 2017; Li & Taylor, 2014; Love & Edwards, 2004; Love et al., 2008; Love, Edwards, Irani, & Goh, 2011; Love et al., 2002; Love, Mandal, et al., 1999) investigated the dynamics of rework and its causal factors in construction projects. The studies proposed systemic models of rework causation using influence diagrams, system dynamics and causal loop models. In software development, Ferreira et al. (2009) presented a system dynamics simulation model to understand the project performance impact of requirements volatility, which is also mediated by the need for rework.

Joglekar and Ford (2005) focused on resource allocation policies as a means to improve product development project performance by reducing project duration. Their model used a combination of system dynamics and the rework cycle. Kiani, Hosseini, and Abdi (2018) evaluated employees' work ethic culture influence on rework and project performance in a construction project and used system dynamics to model and analyze the project. Mitchell and Nault (2007) evaluated how cooperative planning and uncertainty influence rework in concurrent engineering and project delays.

Akkermans and van Oorschot (2016) developed a model based on system dynamics to better understand the trade-off between overlapping product development phases to reduce the development cycle and the risk of having to rework activities, which in turn would increase the development cycle.

2.1.2.4 Document sample analysis synthesis

The rework phenomenon is recognized as part of complex projects. Although rework is necessary to adjust the product being developed, it is also a major source of project performance disruption in terms of cost and schedule (Wynn & Eckert, 2016). The reviewed literature was organized into three main domains: the construction literature, product development literature and project management literature.

The construction literature explored rework as a main topic of investigation in 84 % of the documents being analyzed. The studies positioned rework as a central point of investigation. Thus, the terminology, causes, effects and dynamics of rework were discussed, and empirical studies to better understand the rework phenomenon were featured in the construction literature.

On the other hand, rework was presented as a central topic in only 15 % of the documents analyzed in product and software development literature. The main goal of the product development literature was to find solutions to reduce the product development cycle. The proposed solutions included defining the optimal sequencing of design activities and overlapping sequential activities. However, overlapping implies the risk of rework becoming necessary.

A common point of the product development and construction literature concerns studies that developed simulation tools. Rework was not the central object of these studies, but it was considered a negative risk in a project. Additionally, studies in the product development and construction literature developed simulation tools to perform change propagation analysis in order to manage rework implementation and to mitigate project disruption. The studies suggested that communication plays an important role in mitigating rework in highly concurrent environments.

System dynamics modeling emerged from the reviewed literature as a new lens to understand projects' dynamics, iterative nature and rework cycle. System dynamics was revealed as a complementary tool to the linear process-based perspective of traditional project management. A better understanding of the rework dynamic within projects is expected to promote learning and improvements for future projects by helping management avoid cost and schedule overruns.

2.2 FOUR EMERGING THEMES

The following section presents the themes that emerged from the literature review process. The themes are discussions about the process architecture, concurrency, the project changing environment and the systems thinking approach.

It is a fact that an optimal process architecture results in improved project execution. Additionally, an optimal process architecture is likely to reduce rework because the information flow is optimized. In addition, to further reduce the development cycle duration, a risky alternative is to overlap sequential activities. It is risky because of the strong interdependencies of the project, which increase the likelihood of rework, which in turn can result in the opposite of the desired effect: a longer development cycle duration.

The establishment of an optimal process architecture is necessary for a streamlined information flow. The optimal architecture is comparable to a snapshot of the desirable and ideal project execution sequence. However, during the project life cycle, there are different sources of change that can disrupt the project plan. As presented in the previous section, even in different types of industries, such as construction, software and product development, there are similar causes that result in changes throughout the project, for example, changes initiated by the project sponsors, changes due to errors, changes due to omissions, and changes because the design did not comply with the requirements or quality standards.

As projects are time-constrained, actions to control the project are necessary to overcome the disruption of changing inputs and to keep the project on track to ensure meeting the agreed-upon delivery date and remaining on budget. Here lies another relevant aspect: management decisions are supposed to control the project; however, the decisions are based on the available knowledge and perceptions of the project status, which are featured by the bounded rationality of the decision makers.

In the case of complex projects, which feature a complex structure, uncertainty goals and processes and time-constrained, intuitive decisions to control the project are unlikely to achieve the controlling objectives. Actually, the controlling decisions can turn out to have counterintuitive effects on the project, such as catastrophic cost overruns and delays. An example of a controlling decision action to recover from project delays is the fast-tracking technique, which is the same alternative discussed previously, the overlapping of sequential activities to reduce project duration. However, the literature indicates that project recovery plans that rely on overlapping sequential activities in complex projects give rise to reinforcing feedback loops. To properly understand the behavior of the complex projects and apply the proper controlling actions, system dynamics modeling can be used.

The four themes that emerged from the literature review process are discussed below.

2.2.1 Process architecture

The process architecture theme emerged from the literature review analysis, and its importance was revealed in the different industry samples discussed in the preliminary analysis, including construction (Alarcón & Mardones, 1998), software (Radice et al., 1985) and product development (Eppinger et al., 1994). In addition, this theme is correlated with project performance because an optimized process architecture for a project may favor better decision making (Tang, Zheng, Li, Li, & Zhang, 2000) and reduce manufacturing waste and the need to redo activities (Stark, 2005), which in turn improves the overall project performance (Love, 2002).

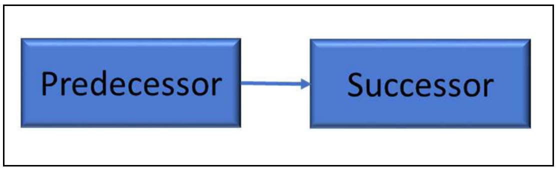
Techniques to define an optimal process architecture were proposed at the end of the 1950s. One was the program evaluation and review technique (PERT), proposed to accelerate the Polaris missile development project of the US Navy (Boulet, 2006; K. Clark, Chew, Fujimoto, Meyer, & Scherer, 1987). PERT was primarily used for research and development projects (Meredith & Mantel, 2011).

PERT seeks to establish an activities network based on their duration and start and finish date constraints (Boulet, 2006) and their information dependency (Parraguez et al., 2016; Yang et al., 2012). The technique considers uncertainties when estimating the activity duration and the consequent project duration, and it suggests that the activity network should be estimated in three scenarios: (1) the optimistic scenario, in which the project completion time is the earliest possible time; (2) the pessimistic scenario, in which the project completion time is the latest possible time; and (3) the scenario in which the project completion time is the most likely actual completion time (Kusiak et al., 1995).

The activities network is input information for the project schedule definition and is determined by the information dependency between the activities. When an activity (labeled successor) depends on the output of other activities (labeled a predecessor), this means that there is information dependency between the successor activity and the predecessor activity (Parraguez et al., 2016). In addition, it determines the information flow, in which the predecessor activity must at least be initiated, and then, when the output required by the successor activity is delivered, the successor activity can start. Consequently, the activities are expected to be performed in sequence, as represented in Figure 2.5.

Figure 2.5

Sequential and dependent activities



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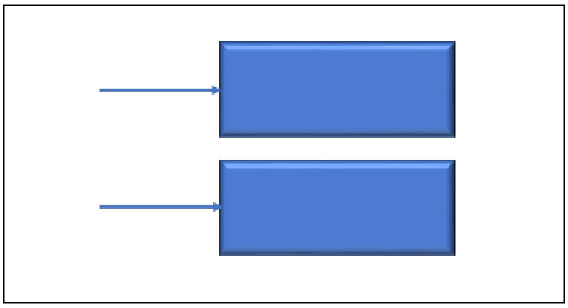
On the other hand, some activities can be performed independent of the output information of the other activities; thus, they can be performed in parallel, as represented in Figure 2.6 (Ulrich & Eppinger, 2012). Therefore, after assessing the information dependency, it is possible to determine the network of activities.

Figure 2.6

Parallel and independent activities



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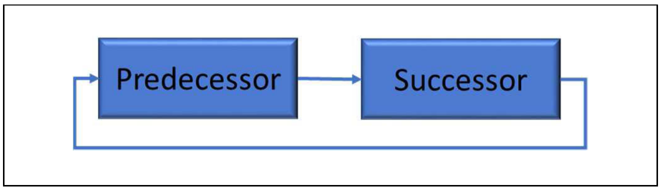
The critical path method (CPM) is similar to PERT; indeed, the two techniques were proposed about the same time. Both of them (1) define the activities network; (2) identify the critical path, which is the project activities path that determines the project final date or project duration; and (3) analyze the activities that have slack, which means that they can be delayed and will not impact the project final date (Meredith & Mantel, 2011).

However, in contrast to PERT's three scenarios of activity duration estimates and the use of PERT in research and development projects, CPM was proposed for civil construction projects (Meredith & Mantel, 2011). This method considers cost trade-offs to accelerate the project completion time (Kusiak et al., 1995; Tang et al., 2000). In CPM, the activity time and cost are often specified on the basis of two scenarios: (1) normal and (2) “crashing”. In the “crashing” scenario, the possibility of reducing the activity duration by means of extra expenditure, such as authorizing the allocation of more resources (extra hours and extra staff, for example), is assessed (Meredith & Mantel, 2011).

Although PERT and CPM are useful tools for determining the activities network, some studies (Eppinger et al., 1994; Gunawan, 2008; Kusiak & Wang, 1995; Parraguez et al., 2016; Yang et al., 2012; Yassine et al., 2001) have found that these tools are not good for managing interdependent or coupled activities, which are those activities that should receive feedback from a successor activity in order to be completed (Yang et al., 2012); such activities are also called iterative activities, as presented in Figure 2.7. In addition, some activities should exchange information continually so that both of them can be completed (Browning & Eppinger, 2002); these are also called interactive activities, as in Figure 2.8.

Figure 2.7

Iterative activities



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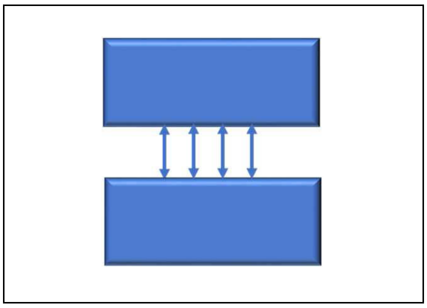
Interdependent activities are common in product development projects due to the complex project activities network (Browning & Eppinger, 2002; Gunawan, 2008; Parraguez et al., 2016; Yang et al., 2012). Additionally, the human bounded rationality makes it impossible to consider all the design requirements and transform them directly into an optimum design without going through an iterative process (Yassine & Braha, 2003). Thus, coupled relationships between activities are a more realistic way to grasp the product development (Eppinger et al., 1994).

Figure 2.8

Interactive activities



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Some authors (Browning, 1998; Browning & Eppinger, 2002; Chai, Du, Zhang, & Su, 2011; Cho & Eppinger, 2001; Forbes, Fleming, Duffy, & Ball, 2003; J. F. Maier et al., 2014; Shekar, Venkataram, & Satish, 2011; Tang et al., 2000; Yang et al., 2012; Yassine, 2004; Yassine et al., 2001) proposed methods and tools based on the design structure matrix (DSM) to optimize the process architecture on the basis of three categories of relationship between activities: dependent (sequential), independent (parallel) and interdependent (coupled). An optimized process architecture favors better decision making in the design process (Tang et al., 2000) and reduces waste and the need to rework activities (Stark, 2005), which in turn improves the overall project performance (Love, 2002).

2.2.2 Concurrency

The product development project is a business process because it involves collaborating to increase the organization revenues by means of delivering new products or improved existing products to the market. As soon as the product is available in the market, the organization has higher chances of guaranteeing profitability (Browning & Eppinger, 2002) and being in a market leader position (Stark, 2005).

The literature suggests that integrated product development may contribute to reducing the development cycle. Although the development process is still sequential overall, the idea is to involve downstream teams in the conceptual and development phases of the project. Thus, downstream teams can collaborate as advisors in such a manner that it is possible to anticipate their requirements and constraints. This is expected to result in more assertive product design proposals by upstream teams (Rauniar & Rawski, 2012; Sommer, Dukovska-Popovska, & Steger-Jensen, 2014). The literature presents this idea as concurrent engineering and as design for X (Amaya, Lelah, & Zwolinski, 2014; Anderson, 2014; Arnette & Brewer, 2017; Bralla, 1999; Morrison, Azhar, Lee, & Suh, 2013; Moultrie & Maier, 2014).

In the 1980s, concurrent engineering was proposed as a potential way to decrease the product development cycle by decreasing the product time-to-market and to overcome the inefficiency of the sequential project approach, such as long development time and high development costs (Tang et al., 2000).

One of the main causes of the sequential project problem is the lack of communication between teams. For example, a team may “pass the design to manufacturing over the wall”, which means, for example, that an engineering design team may pursue its design activities without considering the manufacturing and assembly production capacity (Stark, 2005; Tang et al., 2000). Thus, when the design is transferred to manufacturing, errors and avoidable problems are identified. Consequently, some design errors must be corrected, leading to redesign, and others errors, due to the advanced project stage, are retained in the manufacturing process and will be ever present in the product life cycle, resulting in manufacturing inefficiency (Kennedy et al., 2014).

Anderson (2014) goes further in problem cause identification by attributing this problem to how engineering students are taught in college. Students are usually taught to design parts of a product and not the entire product. Thus, when they became professionals, they behave in the same way they were taught in college, resulting in problems related to the integration of the designed parts into a whole product. Another other relevant aspect mentioned by the author is that students are taught to design for functionality but not for manufacturing in terms of assembly and cost.

Concurrent engineering, also called simultaneous engineering or even parallelization (Schabacker, Gericke, Szélig, & Vajna, 2013), is not exclusive to solving problems between design and manufacturing teams. The concurrent engineering definition presented by the Institute for Defense Analysis in 1988 considered that engineering design teams should be aware of the product life cycle and the project management targets, including cost, delay and scope, from the beginning of the product development (Stark, 2005). The idea of involving multidisciplinary departments, such as purchasing, marketing, production, and technical support, in product development is intended to reduce downstream supply-chain problems, which in turn contributes to project performance (Stark, 2007).

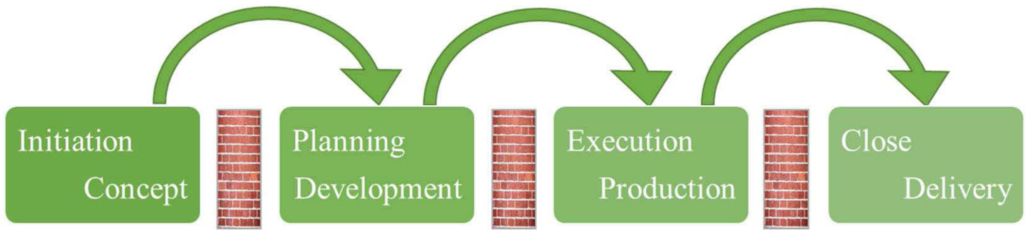
Thus, some problems resulting from the lack of communication between downstream teams can be overcome if those teams are involved earlier, before the project execution phase where they have to perform their activities (Rauniar & Rawski, 2012; Shekar et al., 2011). The downstream teams will not be responsible for the design engineering activity but will act as advisors (Kennedy et al., 2014).

When there is involvement of the downstream teams, the delivered outputs are expected to be suitable for their production capabilities (Moultrie & Maier, 2014) thus avoiding situations such as misunderstandings and errors. This approach is likely to contribute to the improvement of the product development project efficiency.

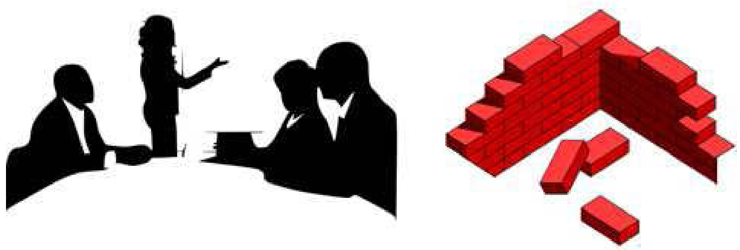
This idea is illustrated in Figure 2.9, where Figure 2.9 (a) represents the traditional sequential product development project, highlighting the idea of passing the project information over the wall. In Figure 2.9 (b), the product development project is still sequential but includes the integration of downstream teams during the conceptual and development phases, meaning, before the production phase.

Figure 2.9

Concurrent engineering and integrated product development



(a) Traditional, purely sequential product development project.



(b) Sequential product development project based on concurrent engineering principles.

(Melo, 2019)

Therefore, to achieve reduced time-to-market, it is necessary that product development take advantage of concurrent engineering because it fills the communication gaps throughout the product and project life cycles by performing not only sequential but also concurrent activities.

2.2.2.1 Overlapping sequential activities as process architecture optimization

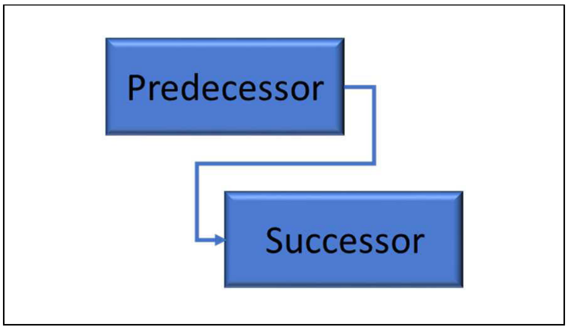
The combination of the themes of process architecture, concurrent engineering and product development as a business process brought to light a research stream on concurrent engineering that seeks to expedite the development cycle even more than the approach of an optimal project process architecture and integrated product development (Dehghan & Ruwnapura, 2014).

The idea is to overlap sequential activities, also called fast tracking, parallelization and, if related to the engineering environment, concurrent engineering (Dehghan & Ruwnapura, 2014). The purpose is to compress the product development cycle even more, as depicted in Figure 2.10. Initially, overlapping sequential activities was expected to be a potential solution to overcome the inefficiency of the overall sequential project. However, many studies have argued that overlapping may lead to counterintuitive effects, leading to longer and more costly product development cycles (Kennedy et al., 2014).

When overlapping activities that should be sequential, the project assumes a risk of reworking downstream activities later. When overlapping occurs, the upstream input information is generally not necessarily entirely available or mature. Additionally, the dependence between activities is modified into a coupled dependence relationship, which can result in a longer duration of the downstream activities (Krishnan et al., 1997). Thus, overlapping sequential activities may expose the project to a greater risk of not achieving cost and schedule constraints, which can worsen when the project process architecture is not carefully assessed (Browning & Eppinger, 2002).

Figure 2.10

Overlapping activities



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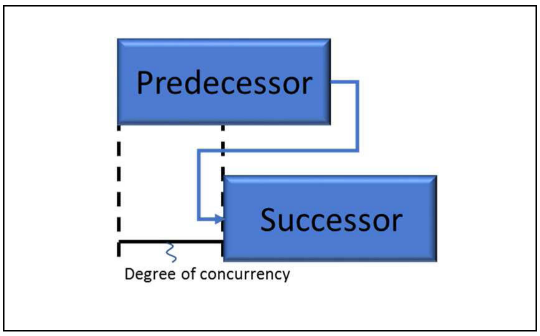
This risk was translated into two concepts proposed by Krishnan et al. (1997): evolution and sensitivity. The evolution concept takes into account the probability of changes in the information from the upstream team due to information maturity. The sensitivity concept assesses the impact on the downstream teams of changes in the upstream team information. The challenge is to determine the appropriate degree of concurrency between tasks, as represented in Figure 2.11, so as not to undermine the efforts to reduce the development cycle by generating rework due to changes in the upstream team information (Yassine & Braha, 2003).

Figure 2.11

Degree of concurrency



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Yang et al. (2012) explicitly discussed the risk to the schedule and cost of projects of overlapping sequential activities. They proposed a mathematical model to optimize the activity sequencing considering the overlapping of sequential activities and evaluated how much work should have been completed in the predecessor activity in order to transfer information for the successor activity.

A qualitative analysis of the risk of overlapping sequential activities, also named fast tracking, was presented by Dehghan and Ruwnapura (2014) for construction projects. The authors highlighted that efforts to overlap sequential activities should be made for activities that form the project critical path; otherwise, the project duration will not be reduced.

Therefore, overlapping sequential activities is a trade-off between reducing the development cycle and costs and the risk of reworking downstream activities if the upstream input information needs to be changed (Yang et al., 2012). If downstream rework is necessary, it may undermine the chances to reduce the development cycle and time-to-market, consequently not achieving the intended goal and instead making the project longer and more expensive (Browning & Eppinger, 2002; Cho & Eppinger, 2001; Lévárdy & Browning, 2009; Yassine, 2004; Yassine et al., 2001).

2.2.2.2 Overlapping sequential activities as a schedule control action

Overlapping sequential activities, also known as fast tracking (Dehghan & Ruwnapura, 2014), is a common practice for managers aiming to recover project schedule (Sterman, 2000). According to Eden, Williams, and Ackermann (2005), projects for which the schedule is underestimated are often exposed to early fast-tracking recovery plans. However, studies have shown that even when management actions are well intentioned, there are side effects caused by detrimental or excessive overlapping (Lin et al., 2008; Lyneis & Ford, 2007) that can lead to project management catastrophes.

Researchers have identified other side effects associated with overlapping, mainly when it is a recovery alternative, such as a rescue plan, applied to an ongoing project. The action of overlapping sequential activities results in altering the relationship between activities. Thus, a relationship that was dependent or sequential is modified to an interdependent or coupled relationship. In addition, according to Williams, Eden, Ackermann, and Tait (1995), interdependent activities may change the overall structure of the process architecture. Thus, the side effect is that increased interdependence results in an increase in the activity duration, consequently increasing the delay in completing the activities (A. Rodrigues & Bowers, 1996).

Moreover, overlapping sequential activities increase the workload in a compressed schedule, consequently demanding more resources. Extra hours or additional staff (Lyneis & Ford, 2007; Sterman, 2000) can solve the problem of needing more resources. However, another side effect is that sustaining extra hours results in professional fatigue, reducing the quality of the work and consequently favoring error generation and the need for more rework. On the other hand, additional staff initially reduce productivity because employees who are new to the project need time to learn about the project activities. New employees are also more susceptible to generating errors, thus reducing the work quality and again resulting in the additional side effect of the need for more rework (Lyneis & Ford, 2007; Sterman, 2000).

These side effects appear in the project cyclically and repeatedly. Williams et al. (1995) explained them as a vicious cycle of parallelism, and Kenneth Cooper explained them as a rework cycle (K. G. Cooper, 1980, 1993b, 1993c), further discussed in §2.2.4. The authors used system dynamics modeling to understand these side effects and the overall behavior of complex projects (Sterman, 2000). The cycles are represented in the models as positive or self-reinforcing feedback loops, which can lead the project to unstable behavior, resulting in project management catastrophes.

Ford and Sterman (1998) and Lin et al. (2008) evaluated the process architecture in product development projects using system dynamics to improve project performance. In addition, Love et al. (2002) used system dynamics to better understand change and rework in construction projects, investigating the major factors that may influence project performance.

Therefore, to improve product development project performance and reduce product development cycles, researchers have been studying alternatives since the early 1960s. Among the alternatives is process architecture optimization, followed by attempts to overlap sequential activities to further reduce the development cycle. However, as discussed in §2.2.2.1 and §2.2.2.2, projects are exposed to the risk of reworking downstream activities if the upstream input information needs to be changed. In addition, side effects can result from management decisions to control the project schedule and in turn can lead to increased project cost and duration.

The next emergent theme concerns the project changing environment and the project management approaches to deal with it.

2.2.3 Project changing environment

The ideal project accomplishment would be based on frozen decisions and consequently on feed-forward information flow only. However, along the actual path to project completion, in addition to the feed-forward information flow, there are several sources of upstream information change and downstream feedback information flow that may result in changes (Karniel & Reich, 2009). Indeed, according to some authors, changes are the rule rather than the exception in the context of complex product development projects (Fricke et al., 2000).

Changes due to new information can become available from different sources and in different moments of the project life cycle (Jarratt et al., 2010). Considering the activities executed in the development phase as a reference, examples of upstream sources could be the marketing and conceptual teams. If information from these sources is updated, downstream activities may be impacted. Examples of downstream sources are teams that undertake their activities in the production phase, for example, manufacturing and customer support feedback may concern incompatibility or integration issues (Han et al., 2014). Additionally, there are external project sources, such as customers and authorities (Jarratt et al., 2010).

The need for change during the project can again result in new decisions and new definitions that may impact the executed downstream work cyclically. Even though changes are expected, they are known unknowns that cannot be fully predicted and planned (Karniel & Reich, 2009). Thus, there is a challenge in integrating those new activities into the project. The project is time-constrained, and integrating new activities may result in more workload to be executed in a compressed time frame.

In addition, depending on how those activities are integrated, they can even desynchronize the optimal process architecture previously defined for the project (Karniel & Reich, 2009), causing activities to be executed out of sequence and generating more errors, downstream feedback, activity concurrence, workload and so on. Yassine and Braha (2003) stated that the rate of problems created in a project should be lower than the rate of problems being solved. Otherwise, the project will become unstable and will no longer be able to achieve the targets determined in the project business case.

The recognition of the project change environment gave rise to a research stream in which alternative project management approaches are proposed to deal with this project reality. Another relevant aspect is the susceptibility of a project that is complex. These discussions are presented in the following sections.

2.2.3.1 Alternative project management approaches

Project management best practices proposed in the 1960s seem to still be actual practices in managing projects (Levitt, 2011). Among them is the assumption that a detailed project plan can be prepared in advance and will remain valid until the delivery of the project (Karniel & Reich, 2011; Levitt, 2011). Then, if changes are necessary, efforts will be made to bring the project back to the detailed project plan. The main problem of this approach is that the external and internal dynamics of the project are neglected (Williams, 2005) because the external environment is not stable or predictable and the internal environment is not fully controllable (Levitt, 2011).

Thus, as the project internal and external environments are exposed to uncertainty and change, Love et al. (2002) classified project dynamics as two types: attended dynamics, which are the project behavioral responses to management decisions, and unattended dynamics, which can be internal uncertainties in the project, for example, financial, conflicting objectives, and external uncertainties to the project, as regulations, economic and meteorological conditions.

Product development projects generally follow the staged gate process, also called the waterfall process, due to its ideally unidirectional information flow. To reduce the project risk associated with dynamic conditions, the reduction of the product development cycle is pursued as well as the ability to accommodate changes throughout the project life cycle (Karniel & Reich, 2011; Unger & Eppinger, 2011).

Even though the product development project has a predefined high-level staged gate structure, the detailed development process should be flexible to accommodate the evolving knowledge that emerges during the project life cycle as a result of the validation of the project assumptions and product development process iterations (Karniel & Reich, 2011).

The recognition of the dynamic, uncertain and iterative nature of projects has motivated authors to propose new methodologies and approaches to address this challenge. These methodologies are based on two parameters: how clear the project goals are and how clear the methods to achieve them are (Lin et al., 2008; Turner & Cochrane, 1993). Turner and Cochrane (1993) classified projects as (1) engineering projects with clear goals and methods, (2) product development projects with clear goals but unclear methods, (3) software development projects with unclear goals but clear method, and (4) research and organizational change projects with unclear goals and methods. The author suggested that each project type should be managed according to its categorization.

The project management approaches proposed in the software development domain are important milestones in attempts to overcome the staged gate approach gaps and cope with dynamics and uncertainty. Some examples of software approaches are the spiral model, evolutionary prototyping, and extreme programming (Karniel & Reich, 2011; Unger & Eppinger, 2011); the agile and lean approach according to Cicmil et al. (2006) is also practiced in the software development industry.

Thus, adapted from software approaches, new product development processes have been proposed to accommodate the dynamic, uncertain and iterative features of product development projects (Karniel & Reich, 2011; Lévárdy & Browning, 2009; Torcato, 2012; Unger & Eppinger, 2011).

2.2.3.2 Project complexity

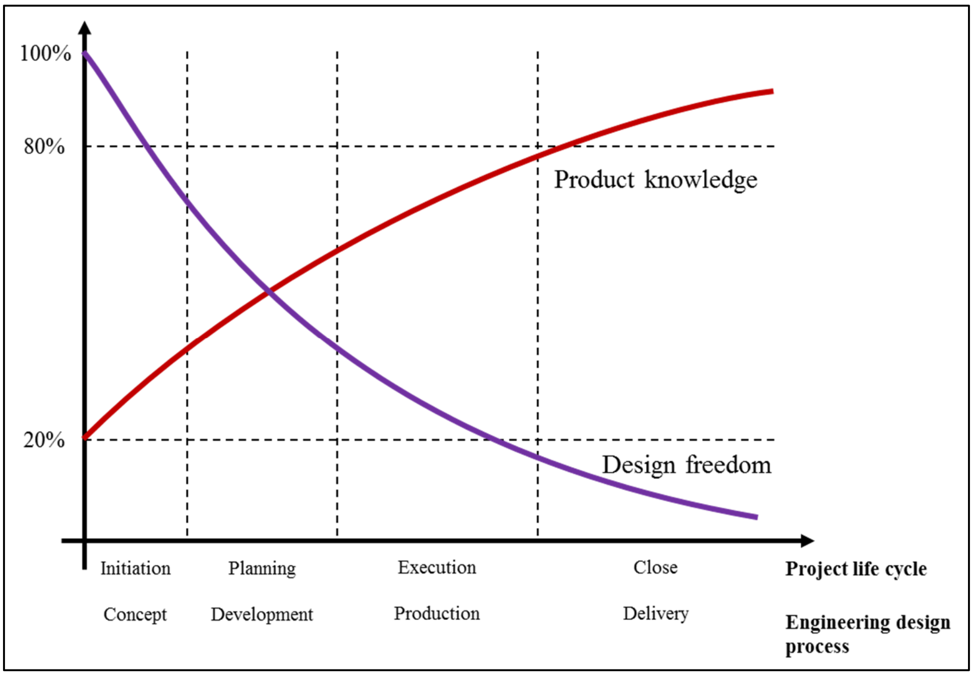
A complex product features an ensemble of parts and systems that are highly integrated so that changes in one part or one system are likely to propagate other changes within the system or in the other systems (Eckert et al., 2004). Consequently, a project to develop a complex product is also complex (Lessard et al., 2014). A complex project features a number of interdependent elements (Williams, 2005), also known as coupled elements (Sterman, 2000). These elements can be, for example, activities, work packages, suppliers, human resources, organization departments and organization sites (Williams, 2005).

According to Eppinger et al. (1994), the design of complex products involves thousands of people and millions of decisions over years. Thus, aligning the different perspectives of decision makers in the project, such as product managers and project managers, is challenging because product managers are concerned with technical decisions to assure the performance of the product, and project managers are concerned with delivering the product on time and on budget but, at the same time, depend on the progress of the product definitions (Karniel & Reich, 2011).

The challenge is reinforced by the dynamic, uncertain and iterative nature of product development projects, depicted by some authors (Karniel & Reich, 2013, p. 19; Ullman, 2010) as the product development paradox, shown in Figure 2.12. The paradox is that even though less knowledge is available at the beginning of the project, when there is a high level of uncertainty, most of the critical decisions are made in this stage. In addition, as a project advances, more knowledge is acquired; however, the freedom to adapt the product design is reduced owing to previous decisions. Nevertheless, changes to the project may be necessary due to the increased knowledge and to the invalidation of the initial project assumptions, resulting in the need for iterations to rework previously performed activities (Karniel & Reich, 2011).

Figure 2.12

Product development projects: design freedom versus product knowledge



(Melo, 2019) adapted from (Karniel & Reich, 2011; Ullman, 2010, p. 19)

In contrast to traditional project management practices, which emphasize detailed planning (Cicmil et al., 2006; Levitt, 2011), the product development paradox is the reason that a product development project cannot be totally planned in advance. As only partial knowledge is available in the beginning of the project, the project knowledge emerges depending on previous decisions and the team iteration results. This indicates the high level of integration between the product decisions and project management (Karniel & Reich, 2011, 2013).

Moreover, traditional project management practice consider that the elements of a work breakdown structure (WBS), meaning the totality of the work to be undertaken in the project, may be incomplete because the project interdependencies and dynamics, i.e., feedback loops, input changes and their associated effects on the product development project, may have been neglected (Cicmil et al., 2006; Williams, 2005). To fill this gap, there is a research stream that studies complex projects as complex systems. According to Williams (2004), the behavior of a complex system cannot be understood by the analysis of its individual parts, which gave rise to the last theme that emerged from the literature review analysis: the systems thinking approach.

2.2.4 Systems thinking approach

Consultants and researchers have been trying to better understand complex project behavior, as in the contributions of Kenneth Cooper from PA Consulting (K. G. Cooper, 1980), Professor John Sterman from the Sloan School of Management at MIT (Sterman, 1992), and Professors Terry Williams, Colin Eden, Fran Ackermann and Susan Howick (Howick, Ackermann, Eden, & Williams, 2017; Williams et al., 1995), initially from the Strachclyde Business School in Glasgow.

The initial motivation of the aforementioned consultants and studies was litigation processes in which companies that executed complex projects claimed that some amount of the project cost overruns and delays were also the customer's fault, mainly due to delayed approvals and customer requirement changes. To prove this claim, consultants and researchers have been involved in several complex project postmortem reviews. Ultimately, what were initially postmortem assessments were used to better plan and control complex projects (K. G. Cooper, 1980; Howick, 2017; Williams, 2003).

Complex projects, which can also be classified as complex dynamic systems, feature highly interdependent parts and within a changing environment comprising multiple feedback loops, nonlinear cause-and-effect relationships, hard and soft data, the confusion of problem symptoms with the real causes and difficult-to-understand behavior (Sterman, 1992; 2000, p. 22).

Cicmil et al. (2006) suggested that relying only on traditional project management approaches, such as CPM, WBS and earned value, is not appropriate for managing complex projects. Indeed, these approaches may mislead project management attempts to properly monitor and control complex projects (Lévárdy & Browning, 2009; Williams, 2005; Williams et al., 1995) because they neglect the project dynamics originating from the high level of uncertainty and interdependence. Moreover, according to Ford and Sterman (1998), they are not able to explain the multiple cause-and-effect relationships.

Systems thinking, which is a holistic approach, has been proposed as a management alternative to handle the complexity and changing environment that are part of complex projects (Jackson, 2003). Its objective is to identify the structures, patterns and mindsets that are behind complex situations and actual events (Senge, 1994).

There are two main systems thinking schools. The first school is soft systems thinking, which aims to solve complex management problems by developing conceptual models. The second school, hard systems thinking, aims to solve well-defined technical problems using mathematical models (Yap et al., 2019).

Among the several systems thinking methodologies, system dynamics methodology has been used to understand complex problem structures so that the behavior of a system can be predicted and modified (Sterman, 2000). System dynamics methodology is generally divided into two parts: the soft, or qualitative part, which includes the statement of the problem, the identification of the variables and the relationship between the variables that comprises the problem, and the hard, or quantitative part, which includes the translation of the soft part into mathematical models that can be transformed into simulation tools (Jackson, 2003, p. 68).

The system dynamics concepts were translated into the project management context in the form of two types of feedback loops: positive feedback loops, which are self-reinforcing processes, and negative feedback loops, which are self-correcting processes. According to Sterman (2000) the dynamic of the systems arises from the interaction of the network of those two types of feedback loops, which are coupled with multiple time delays, nonlinearities and accumulations.

Thus, systems thinking using system dynamics modeling has been used to understand complex project behaviors (Lyneis & Ford, 2007). The system dynamics methodology allows the inclusion of human, environmental, organizational, and technical aspects in the model (Love, Irani, & Edwards, 2003) as well as variables such as team frustration, time pressure, market changes and management actions (Cicmil et al., 2006).

Four main topics were identified in the literature concerning rework and systems thinking approach. The first concerns the rework cycle and its negative impacts on project performance as described by K. G. Cooper (1980). The second concerns the vicious cycle of parallelism, which is also related to rework, as presented by Williams et al. (1995). The third concerns system dynamics models of product development projects. The last topic concerns relevant studies in the construction literature that investigated the dynamics of rework and its causal factors. These four ideas are discussed in the following sections.

2.2.4.1 Rework cycle

The rework cycle is a positive feedback loop that assumes that the project activities are not perfectly executed. Thus, the imperfect remaining portion of the activities needs to be reworked. Additionally, the rework cycle depends on the level of staff productivity and delays in identifying imperfections (K. G. Cooper, Lyneis, & Bryant, 2002).

In the rework cycle, the project activities in the beginning of a project can be represented as a stock of activities “to be done”. Consequently, when those activities are completed, they are transferred to another stock of activities that are “done”. However, the questioned by K. G. Cooper (1993a) is whether the activities considered “done” are “really done”. The author observed that the quality of the activity performed may not be perfect and that staff productivity can vary during the project phases, resulting in an intermediate stage between “to be done” and “really done”.

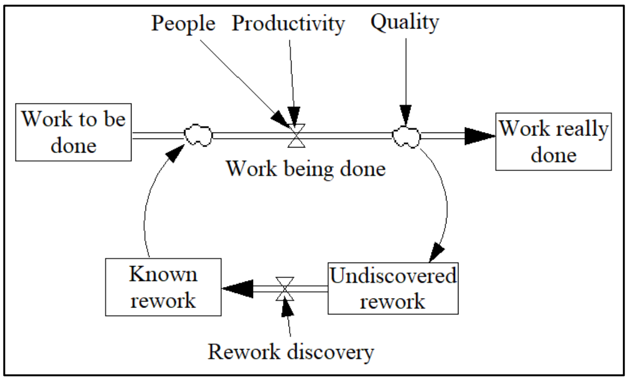
This intermediate stage concerns the activities for which the imperfect portion needs to be corrected. The challenge is to discover those imperfections, which gives rise to backlog of “undiscovered rework” and “discovered rework”. Imperfections are usually captured by downstream teams, and the more time it takes to discover them, the more damage they may cause to the project performance (K. G. Cooper, 1993a). Figure 2.13 presents the rework cycle modeled as a stock-and-flow structure, which is a quantitative system dynamic modeling method.

The rework cycle effects can be exacerbated when the project is behind schedule by management decisions that are made to control and adjust the project outputs. In this case, the control objective is to bring the project back to the planned schedule to meet the target delivery date. However, due to the lack of awareness concerning the rework cycle, these management decisions may result in counterintuitive effects, such as significant project disruptions and delays (Eden et al., 2005).

For example, adding supplemental staff to accelerate a project may result in more delay instead of improving the project progress. If the staff are new, their productivity and work quality will be low until they learn the activity that they are expected to perform. Alternatively, if the supplemental staff hours are obtained by sustained overtime, it may lead to staff to fatigue, also reducing productivity and work quality (K. G. Cooper, 1994). Both examples reinforce the rework cycle and worsen the project situation. In the end, these management decisions lead to more money spent without recovering the desired project progress.

Figure 2.13

Rework cycle



Source: (K. G. Cooper, 1993a)

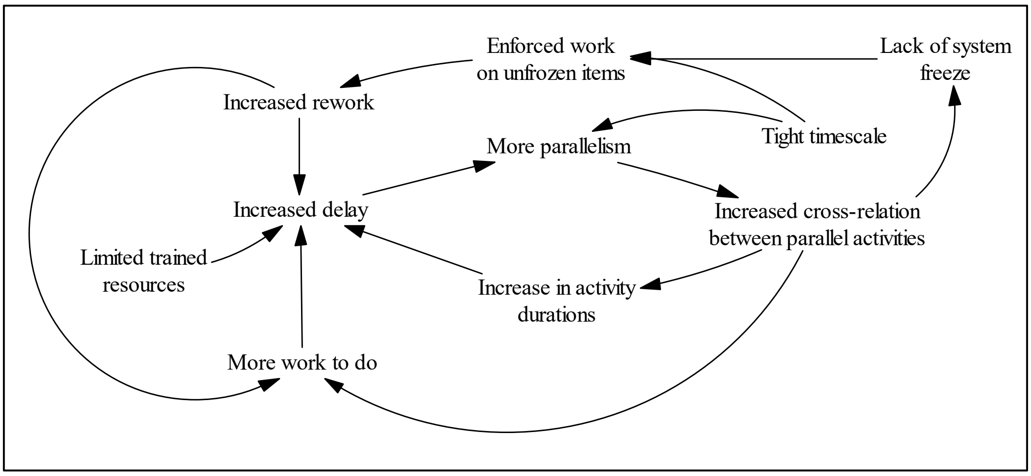
2.2.4.2 Vicious cycle of parallelism

In the same direction is the vicious cycle of parallelism, another positive feedback loop proposed by Williams et al. (1995). The authors observed that for complex projects that are time constrained and behind schedule, the situation may be aggravated by management decisions made in an attempt to control the project schedule.

According to the authors, when project managers authorize the parallelization of interdependent activities, it increases the duration of the activities. However, when a project is time-constrained, more parallelism is added to recover the schedule slippage, which in turn results in more work to be done, again increasing the duration of the activities in a reduced time frame, increasing the rework and so on (Williams et al., 1995). This vicious cycle of parallelism is presented in Figure 2.14. Eden et al. (2005) observed that in projects in which the schedule is underestimated, the parallelism of interdependent activities is needed earlier.

Figure 2.14

Vicious cycle of parallelism



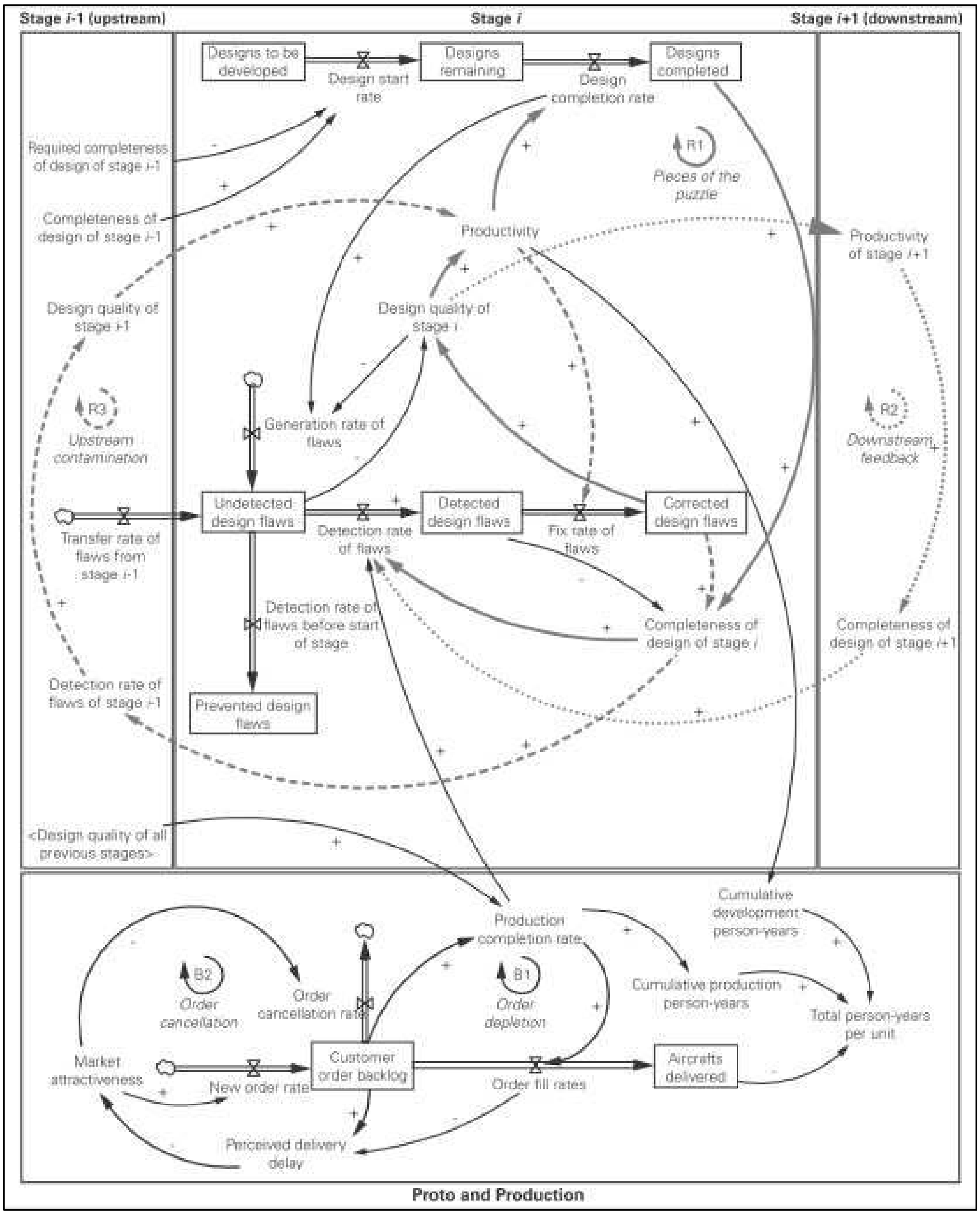
Source: (Williams et al., 1995)

2.2.4.3 Systems thinking and product development literature

Studies using hard systems thinking were found in the literature on product development. Some authors (Akkermans & van Oorschot, 2016; Ford & Sterman, 2003b; Lin et al., 2008) proposed system dynamics simulation models to understand the trade-offs between overlapping design activities to reduce the development cycle and the risk of having to rework downstream activities due to upstream changes. Figure 2.15 presents the model of Akkermans and van Oorschot (2016).

Figure 2.15

System dynamics simulation model of a four-stage aircraft development program



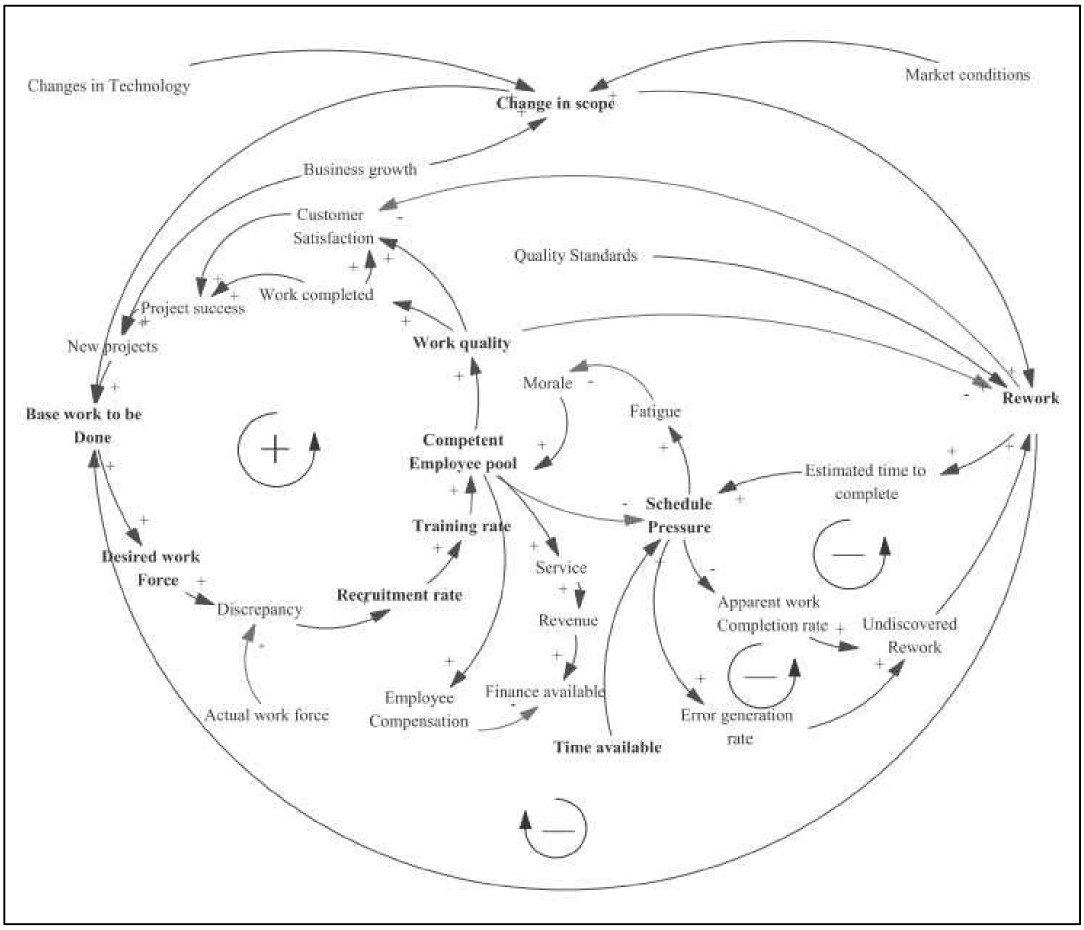
Source: (Akkermans & van Oorschot, 2016)

In the same direction, L. L. R. Rodrigues et al. (2006) developed a system dynamics simulation model using soft and hard systems thinking.

Figure 2.16 presents the causal loop model proposed as a soft systems thinking tool to identify the main variables and their interrelations. The hard systems thinking part of the model was based on system dynamics methodology, as shown in Figure 2.17. The study objective was to understand the project dynamics when changes in the scope happened because of the development of new technology. Rework was identified as a dynamic factor, i.e., a variable in the model.

Figure 2.16

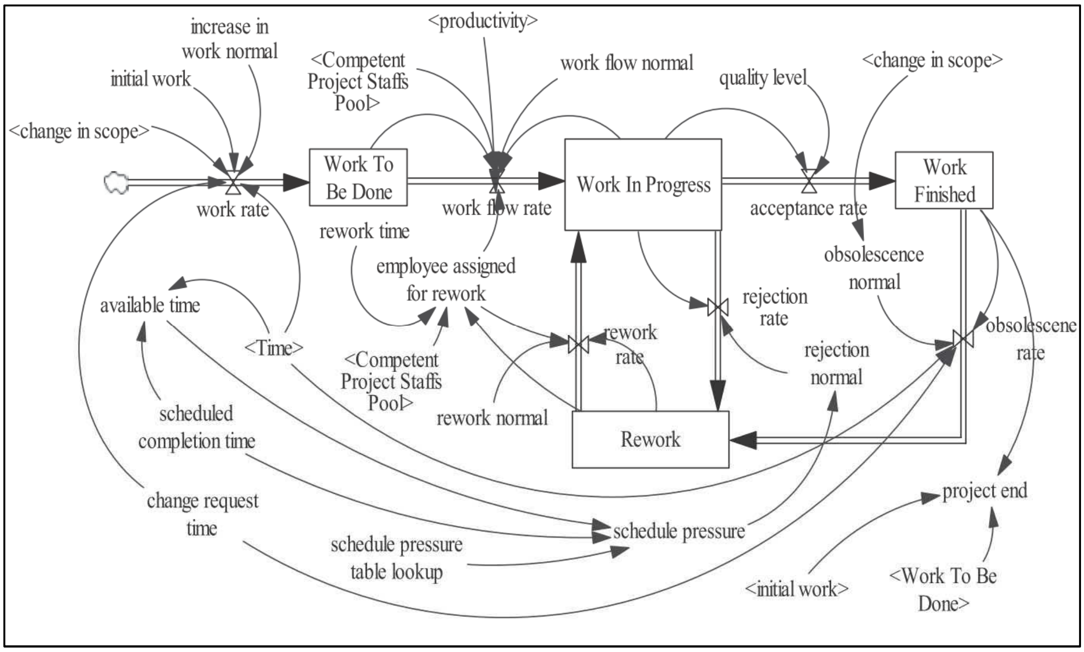
Causal loop model of the dynamics of new product development



Source: (L. L. R. Rodrigues et al., 2006)

Figure 2.17

System dynamics simulation model of new product development



Source: (L. L. R. Rodrigues et al., 2006)

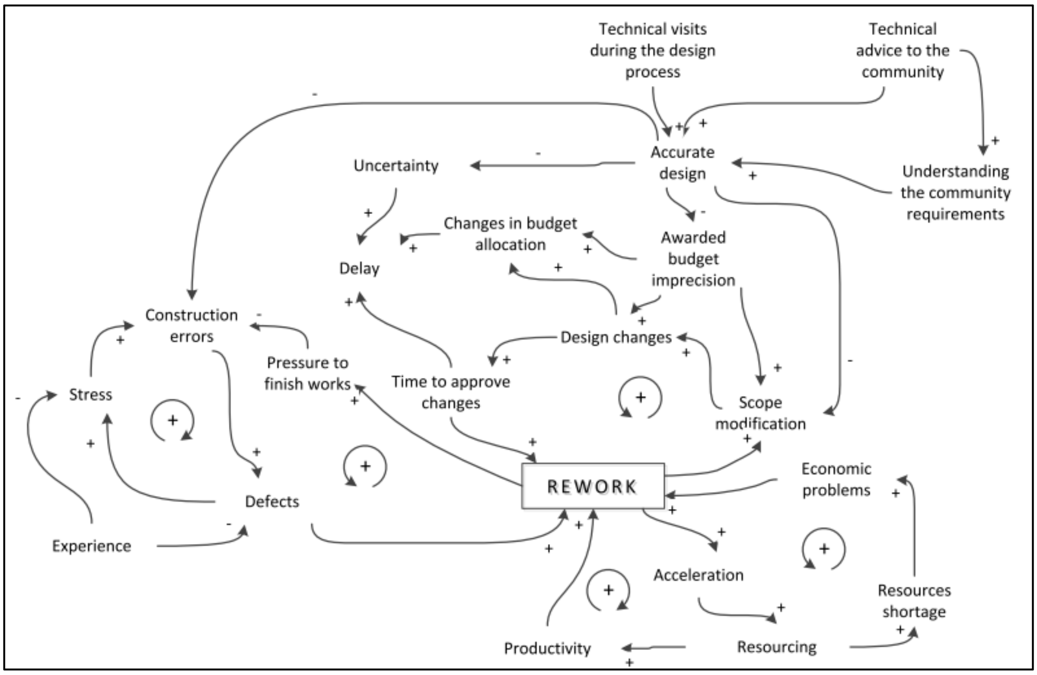
2.2.4.4 Dynamics of rework in the construction literature

As discussed previously, the literature on construction projects has recognized rework as a problem that negatively impacts project performance. Consequently, the causes and effects of rework have been investigated in the construction literature. However, studies have also shown that the causes of rework are not a list of root causes; in contrast, they are a network of multiple causes that influence each other (Yap et al., 2019). Indeed, Love, Edwards, and Smith (2016) argued that focusing only on finding independent causes of rework and ignoring the context and the dynamics involved may lead to incorrect conclusions that do not contribute to solving the rework problem.

The construction literature has evidenced a lack of systematic knowledge concerning the dynamics of rework (Forcada et al., 2017). Indeed, the importance of investigating the nature of rework causation lies in the possibility of understandingthe associated dynamics, meaning the internal structure of rework, the effects of which have been proven to contribute to project cost-schedule overruns (Safapour & Kermanshachi, 2019). The dynamics of rework are associated with the interdependencies among the critical variables related to it. Love et al. (2016) supported the idea that if rework is to be addressed, it is necessary to alter or influence the dynamics of rework by changing project processes and policies so that the undesirable effects can be mitigated.

Studies have used systems thinking in seeking to fill this gap in the construction literature. Studies have proposed systemic models using influence diagrams to represent the rework causation based on analyses of offshore hydrocarbon projects (Love et al., 2011), highway projects (Forcada, Rusiñol, MacArulla, & Love, 2014) and urban renewal projects in Colombia (Forcada et al., 2017); one of the models is presented in Figure 2.18.

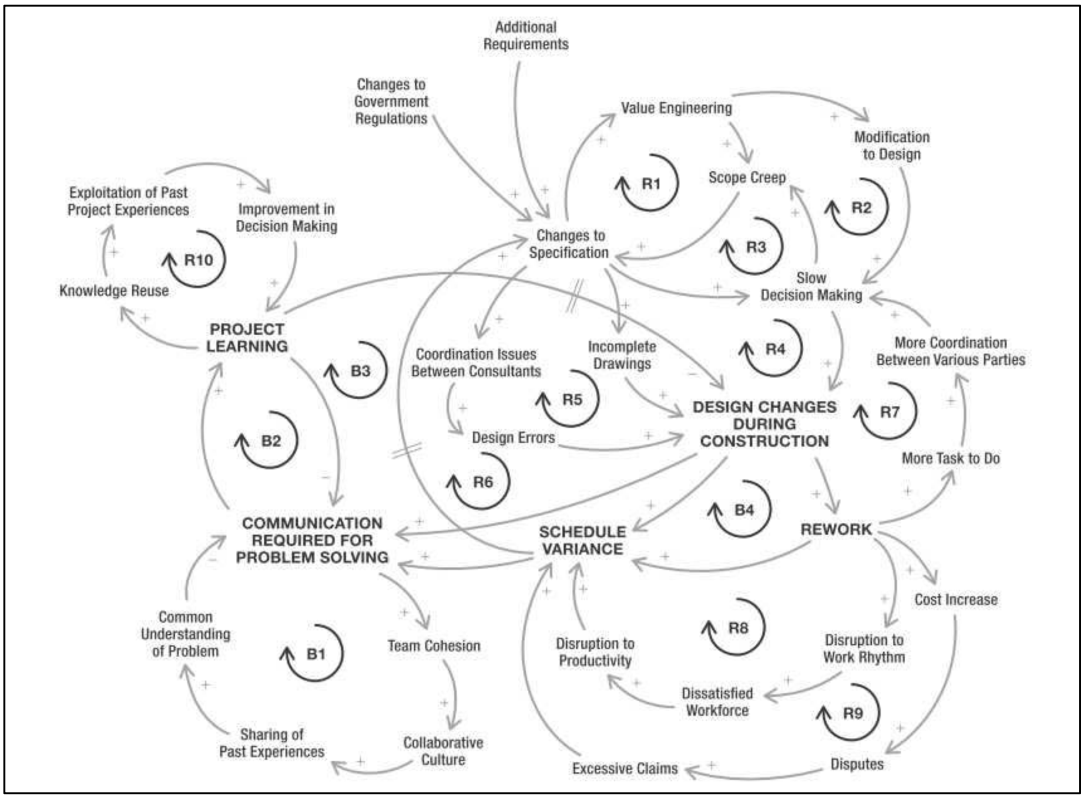
Figure 2.18
Systemic model of rework causation for urban renewal projects in Colombia



Source: (Forcada et al., 2017)

Burati, Farrington, and Ledbetter (1992) found that 78 % of rework was due to design changes, which in turn represented 9.5 % of the project cost of the nine construction projects being investigated. Thus, Yap et al. (2019) adopted a systemic approach to model design change causation in construction projects using causal loop modeling. The authors also considered the efficacy of communication and knowledge as a strategy to reduce design changes; their model is presented in Figure 2.19.

Figure 2.19
Causal loop model of design change causation in construction projects



Source: (Yap et al., 2019)

The studies presented in this section used soft systems thinking to model the dynamics of rework, and influence diagrams and causal loop models represent the interrelations between the compounding factors of rework causation. Table 2.1 presents the main factors highlighted by the authors as causes of rework in construction projects.

Table 2.1

Main factors highlighted by authors as causes of rework in construction projects

Main factors	(Love et al., 2011)	(Forcada et al., 2014)	(Forcada et al., 2017)	(Yap et al., 2019)
Initial budget			x	
Poor project design, errors/discrepancies in design documents			x	x
Inexperienced workers, poor skill levels		x	x	
Scope change, poorly defined scope, addition to/omission from scope	x	x		x
High complexity		x		
Unexpected underground services		x		
Unrealistic schedule	x			
Design changes, modification to design	x			x
Coordination problems	x			x
Value engineering				x
Change in requirement				x
Additional requirements				x
Changes in government regulations				x
Design omissions/incomplete drawings				x
Slow decision making				x

(Melo, 2019)

Thus far, no studies were found in the product development literature investigating the dynamics of rework. Curiously, although the construction literature recognizes rework as a problem, there are few studies available concerning the dynamics of rework, which makes it difficult to propose generalizations and predictability to address the rework problem (Forcada et al., 2017; Yap et al., 2019).

2.2.5 Four emerging themes summary

The four themes discussed in this section emerged from the preliminary research for this study. The main conclusions for each of the four themes are presented in Table 2.2.

Table 2.2

Main conclusions about the four emerging themes

Section	Highlights
§2.2.1 Process architecture	Process architecture evaluates the dependencies between the activities to be undertaken in the project. On the one hand, the traditional project management research stream classifies activity dependency as dependent (sequential) and independent (parallel). On the other hand, the DSM research stream presents a third type of dependency, the interdependence (coupled) that is common in product development projects. An optimized process architecture may improve the project performance because it favors better decision making and reduces the need of rework.
§2.2.2 Concurrency	The product development project has a structured sequential nature. To overcome its disadvantages and to reduce time-to-market, concurrent engineering has been an alternative because it may improve the communication between project stakeholders, anticipate downstream teams' requirements and constraints; and increase the product design team's awareness of the product life-cycle aspects and the project cost and schedule targets. In this context, two research streams unfolded: Overlapping sequential activities as process architecture optimization and Overlapping sequential activities as a schedule control action
§2.2.3 Project changing environment	An ideal project management environment is based on frozen decisions and feed-forward information flow. However, in reality as the input information changes and there is feedback from downstream teams, changes are expected in the project, which in turns cyclically generates the need for new project decisions. The new activities generated due to the changes should be properly accommodated in the project. Otherwise, the execution of the activities out of sequence may generate more changes, starting new cycles.
§2.2.4 Systems thinking approach	A complex dynamic system features nonlinear and interdependent cause-effect relations among its elements. These concepts are translated into the project management context, where management decisions to control the project schedule have been demonstrated to result in counterintuitive effects due to the dynamic nature of complex systems, such as product development projects. A dynamic structure that contributes to project cost and schedule overruns is the one involving the rework phenomenon.

(Melo, 2019)

2.3 THREE RESEARCH STREAMS

The literature presented previously indicates that since the beginning of the 1960s, different approaches have been proposed to improve product development projects. Three research streams are highlighted: the traditional project management practices represented by the PERT, CPM and WBS techniques; the DSM as a tool to better understand project element interdependencies; and systems thinking using system dynamics modeling which takes into account complexity, the changing environment and management decision effects.

All of these research streams seek to improve and reduce the product development cycle and its associated costs. Each plays an important role in improving project performance. Consequently, no individual approach should be discarded; instead, they should be integrated.

2.3.1 Traditional project management research stream

Traditional project management practices are well known and accepted among the practitioners. They have brought to light the importance of standardizing projects and breaking them down into manageable portions. However, when the project elements feature a high level of interdependence and uncertainty, those techniques are not enough to ensure a realistic approach to project management because they are essentially static tools, in contrast to the dynamic nature of this type of project and project environment.

2.3.2 DSM research stream

The DSM research allows a better understanding of complex product development project interdependencies, including the product architecture, project activities and project team aspects as well as the analysis of those elements. Thus, the DSM offers a systemic view of the project in which the interdependencies are not neglected and facilitates the definition of optimized process architecture sequencing, which can be extended to architectures that seek to further reduce the development cycle by overlapping sequential activities. The risk associated to overlapping sequential activities can be minimized if the practice is based on previous analysis.

Even though the DSM is a powerful tool to use in planning complex projects because it takes into account project uncertainty and interdependence, it is still a static tool, analogous to a process snapshot. However, a complex project is exposed to a series of internal and external changes due to its dynamic environment. To adjust the project to assure the desired project output in this dynamic environment, management decisions and actions, which are not covered by the DSM tool, need to be considered as well. Thus, even though the DSM is relevant to assuring an optimal process architecture for a project, it also is not enough to assure realistic project management.

2.3.3 System dynamics research stream

The system dynamics research stream, which investigates the system dynamics applied to project management, seems to be a potential solution to overcome the gaps of the traditional project practices and DSM-related research. System dynamics, which is a systems thinking methodology, has been used to analyze complex projects as complex systems. System dynamics consider the project and the product interdependencies from a holistic perspective. In addition, the system dynamics modeling recognizes the project dynamic environment and the effects of management decisions and actions intended to control the project schedule.

2.3.4 Four emerging themes and three research streams

Table 2.3 presents the four emerging themes from chapter 2 §2.2 from the perspective of the three research streams that emerged from the literature review.

Table 2.3
The four emerging themes versus the three research streams

Research stream/ Four themes	Traditional project management	DSM	System dynamics
Process architecture	Feed-forward One direction only	Feed-forward Feedback	Feed-forward Feedback
	Hard: process-based view	Hard: process-based view	Hard: process-based view Soft: causality map; management controlling actions are considered
Concurrency	Overlapping sequential activities as a schedule control action	Overlapping sequential activities as a process architecture optimization action	Overlapping sequential activities as a schedule control action
Project changing environment	Neglected Changes are considered to happen minimally	Change propagation analysis Proactive approach: change propagation prediction Corrective approach: change propagation assessment	Internal and external project changes are recognized
Systems thinking approach	Static	Static	Dynamic
	Project breakdown structured Project is decoupled in manageable parts	Project is understood as systems Coupled dependencies are recognized	Project is understood as systems Coupled dependencies are recognized

(Melo, 2019)

2.4 THEORETICAL CONTEXT SUMMARY

As presented in chapter 1, even though project management best practices and research have been in place for several years, organizations still struggle to manage complex projects, as shown by the cost-schedule overruns that plague project performance. Table 1.5 listed studies concerning different topics that potentially influence project performance. Among them is the rework phenomenon, which is of interest to this research, specifically EDR in complex product development projects.

The preceding sections of chapter 2 presented an in-depth literature review whose perimeter was defined by four main keywords: rework, project management, product development and change, as illustrated in Figure 2.1. Three industries were identified within the literature review perimeter: product development, software development, and construction. Additionally, four themes emerged from the literature review: process architecture, concurrency, project changing environment and systems thinking approach.

The highlights of the literature review analysis, which allowed the researcher to identify a relevant gap in the literature and propose the research question and research objectives of this study, are presented as follows.

Section §2.2.1 presented studies showing the importance of planning an optimal process architecture in order to mitigate rework occurrence and improve project performance. Section §2.2.2.1 presented several studies about overlapping sequential activities as a strategy to reduce the project cycle; however, the studies revealed the risk of rework being necessitated downstream by upstream changes in the project; depending on the quantity of rework needed, the initial objective of reducing the project cycle could be undermined.

Since the 1960s, consultants and researchers have been trying to understand the behavior of complex projects (K. G. Cooper, 1980; Eden, 1988; Eden, Ackermann, & Cropper, 1992; Forrester, 1968; Senge & Sterman, 1992; Sterman, 1992; Williams et al., 1995). Williams (2005) summarized in a combination of three factors the reasons that complex projects fail when they are managed following traditional project management practices. The three factors are the project's structural complexity, high level of uncertainty and compressed schedule.

Systems thinking has been used to identify the complex project structures that generate the behaviors and patterns of projects that result in cost-time overruns. In addition, according to Lyneis and Ford (2007), even though the behavior of complex projects is fairly well understood, the translation of this knowledge to organizations is lacking, including aspects such as training materials and operationalization methodologies. Management decisions are still made blindly on the basis of short-term results and traditional project management practices (L. L. R. Rodrigues et al., 2006). Additionally, management decisions contribute to project disruptions and delays due to the lack of awareness of complex project dynamics (Howick, Ackermann, Eden, et al., 2017).

Traditional project management tools are, for example, the work breakdown structure, the activities network, the critical path method and the earned value method. Although they are important for project planning and control, they are not enough to properly manage complex projects because they neglect the project dynamics related to the high level of uncertainty and interdependency within complex projects (Cicmil et al., 2006).

Among the dynamic structures identified in the literature that are related to rework and complex project performance are the rework cycle (§2.2.4.1) and the vicious cycle of parallelism (§2.2.4.2), which are positive or self-reinforced feedback loops. Those structures supported authors explanations of project time and cost overruns because they showed that certain management decisions to control project schedules resulted in counterintuitive effects that negatively impacted project performance (K. G. Cooper, 1980; Williams, 2004). Additionally, few studies concerning the dynamics of rework were found (Forcada et al., 2017; Forcada et al., 2014; Love et al., 2011).

Hence, the main conclusion of the literature review analysis is that the rework phenomenon is a challenge for complex projects and is a source of inefficiency that impacts project performance. In the case of complex product development projects, rework in many cases is considered a necessary evil that is unavoidable and intrinsic to the project life cycle (Kennedy et al., 2014). Thus, in this research, rework is investigated as a complex managerial problem because its behavior is not completely understood.

Another conclusion of the literature review analysis is that the construction literature is the main contributor of the actual body of knowledge on rework, including the explicit acknowledgment of the negative effects of rework on project performance and the identification of many rework causes (Eze & Idiake, 2018; Love & Edwards, 2004; Love et al., 2014; Love et al., 2009; Love, Li, et al., 1999; Love & Smith, 2003; Safapour & Kermanshachi, 2019). However, recent conclusions recognized that identifying single root causes of rework has not been effective in addressing the problem (Love et al., 2016; Yap et al., 2019).

This may relate to the complex structure of rework because many causes can trigger rework; however, as the causes are interdependent, they influence each other and complicate the understanding of the phenomenon as well as the proposition of solutions to the problem. Moreover, the causes and effects of rework are not close in time and space; thus, symptoms are confused with causes. Consequently, recognition of the dynamics of rework, meaning the nature of rework causation and the identification of its complex structure, is recommended in addressing the rework challenge in complex projects (Love et al., 2016).

According to Love et al. (2016), investigating rework structures will allow the identification of the behavior patterns underlying the dynamics of rework. Thus, the rework structure could be influenced to improve the project performance and to allow the development of theories and generalizations concerning the dynamics of rework.

Finally, during the literature review process, as far as the researcher is aware, no studies were found concerning the dynamics of rework in complex product development projects. To fill this gap in the literature, **this study intends to investigate the**

dynamics of engineering design rework in complex product development projects to better understand the phenomenon.

2.5 RESEARCH QUESTION AND RESEARCH OBJECTIVES

In light of the literature review analysis, three main factors are considered in the investigation of the dynamics of rework. The first is the product development process, which includes the previous discussions about the process architecture (§2.2.1), integrated process development and process concurrency (§2.2.2); this factor is associated with a planning or static aspect. The second is the project dynamics associated with the changing environment (§2.2.3) in which the product development project is immersed; it is a dynamic factor. The third is the management decisions that are needed to manage the project and its performance (§2.2.4); it is a controlling factor that is dependent on the two other factors. Table 2.4 summarizes these three factors.

Table 2.4

Dynamics of rework main factors based on the literature review analysis

Main factors	**Literature review insights**
Static	Development process architecture, integration between development teams (communication), planned concurrency between activities
Dynamic	Product knowledge evolution, invalidation of upstream assumptions, downstream feedback
Controlling	Fast-tracking sequential activities

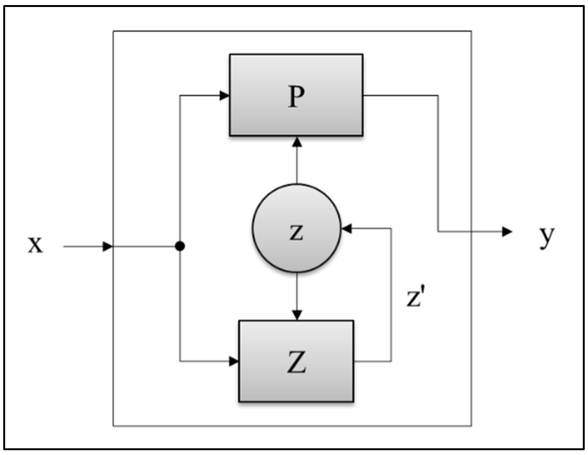
(Melo, 2019)

Considering the three main factors presented in Table 2.4, the nontrivial machine presented by von Foerster (1984) and discussed by Tsoukas (2017) as a representation of organizational complexity seems to be an appropriate initial representation of the dynamics of rework. The reason relies on the functioning of the nontrivial machine, which is aligned with the aforementioned three factors that represent the basis for better understanding the dynamics of rework in complex product development projects in this study.

From the perspective of the nontrivial machine, concepts such as stability and change, routines and recursive interaction they coexists rather than considering only predictable behaviors and excluding stochastic ones from the analysis. The output of the nontrivial machine depends not only on the machine input and the transformation processes but also on the actual state of the machine. This is the main difference between a trivial and nontrivial machine; the actual state represents the acknowledgement of the presence of changes, which is what makes the machine output hard to predict (Tsoukas, 2017).

An adapted version of von Foerster (1984) nontrivial machine is presented in Figure 2.20. The machine has an input and an output, "**x**" and "**y**", respectively. Inside the machine are two functions, "**P**" and "**Z**". The machine actual state and the machine future state represented by "**z**" and "**z'**", respectively. Additionally, the arrows represent how the machine elements influence each other. The nontrivial machine does not neglect the interconnected network of feedback loops and the interactions between the elements that are part of the system (Tsoukas, 2017). For these reasons the nontrivial machine functioning seems to be a suitable representation of the dynamics of rework and a preliminary conceptual framework for this study.

Figure 2.20
Preliminary conceptual framework



Source: adapted from (von Foerster, 1984)

The element “P” represents the expected product development processes and the associated planning aspects. The element “Z” represents the management decisions necessary to manage the project performance. The actual state “z” represents the changing environment of complex projects. The element “x” represents the triggers of the dynamics of EDR, and “y” represents the negative impact of the dynamics of EDR in the product development project performance, meaning time and cost.

In summary, the reality of a complex product development project is in alignment with the functioning of the nontrivial machine. The correspondence of the main factors of the dynamics of rework and the machine elements is presented in Table 2.5.

Table 2.5

Main factors of the dynamics of rework and the nontrivial machine elements

Dynamics of EDR main factors	**Nontrivial machine elements**
Static	P
Dynamic	z, z’
Controlling	Z

(Melo, 2019)

Table 2.6

Preliminary conceptual framework elements

Preliminary conceptual framework elements		**Literature review insights**
x	Triggers of the dynamics of EDR	Project budget, schedule and scope, additional and changed requirements, design change, professional experience, complexity
P	Product development project static factors	Development process architecture, integration of development teams (communication), planned concurrency between activities
z	Product development project dynamic factors	Product knowledge evolution, invalidation of upstream assumptions, downstream feedback
Z	Product development project performance controlling factors	Fast-tracking sequential activities
y	Product development project performance	Project cost and development cycle duration

(Melo, 2019)

Based on the literature review analysis and the preliminary conceptual framework proposed in Figure 2.20, the research question that this study seeks to answer is as follows:

What is the dynamics of engineering design rework that negatively impacts the performance of complex product development project?

To answer the research question, two research objectives are defined and presented as follows:

Objective 1: Identify the variables that make up the dynamics of engineering design rework in complex product development projects.

Objective 1 is divided into five subobjectives as presented in Table 2.7.

Table 2.7
Objective 1 and subobjectives

Objective 1	
1.1	Identify the variables concerning the element "x" in the conceptual research framework (Figure 2.20), which represents the triggers of the dynamics of rework.
1.2	Identify the variables concerning the element "P" in the conceptual research framework (Figure 2.20), which represents the static factor associated with the product development project (Table 2.4).
1.3	Identify the variables concerning the element "z" in the conceptual research framework (Figure 2.20), which represents the dynamic factor associated with the product development project (Table 2.4).
1.4	Identify the variables concerning the element "Z" in the conceptual research framework (Figure 2.20), which represents the controlling factor associated with the product development project performance (Table 2.4).
1.5	Identify the variables concerning the element "y" in the conceptual research framework (Figure 2.20), which represents the impact of the dynamics of EDR in the product development project performance.

(Melo, 2019)

Objective 2: Identify the feedback relationships between the variables that comprise the dynamics of the EDR in complex product development projects

Objective 2 is divided into five subobjectives as presented in the Table 2.8.

Table 2.8
Objective 2 and subobjectives

Objective 2	
2.1	Identify feedback relationships between elements (x) and (P).
2.2	Identify feedback relationships between elements (x) and (Z).
2.3	Identify feedback relationships between elements (z) and (P).
2.4	Identify feedback relationships between elements (z) and (Z).
2.5	Identify feedback relationships between elements (P) and (y).

(Melo, 2019)

Achieving the objectives of this research and answering the research questions are expected to result in academic and managerial contributions.

The academic contributions rely on returning the knowledge learned from the results of this study to the three research streams previously discussed concerning traditional project management (§2.3.1), the DSM (§2.3.2) and system dynamics modeling (§2.3.3). In the literature review, few studies concerning the dynamics of rework were found, and as far as the researcher is aware, no studies on complex product development were found except in the construction literature.

On the other hand, the managerial contribution relies on making better management decisions to improve project performance by taking into account knowledge of the mechanisms underlying the dynamics of rework. Understanding the dynamics means understanding its functioning so that it is possible to influence the mechanism that generates the results. This includes understanding the short- and long-term effects the management decisions and understanding the organizational policies that may lead to high-leverage results.

For the sake of simplicity, from this point on, the dynamics of EDR will be written as dynamics of rework.

CHAPTER 3 - METHODOLOGY

The objective of this chapter is to present the researcher's methodological position and research approach as well as the research design, the sampling strategy, and the strategy for data collection and data analysis that allowed the researcher to answer the research question and achieve the research objectives. The content of this chapter follows the research onion model proposed by Saunders et al. (2012). The chapter closes with a presentation of the research design quality and the ethical aspects of the research.

3.1 METHODOLOGICAL POSITION AND APPROACH

This research recognizes the dynamics of rework as nontrivial. One reason is that the EDR is embedded in product development projects as part of a continuously changing reality. The changes come from different sources and at different moments of the project life cycle (Godlewski et al., 2012). To better grasp this dynamic reality, this research adopted an organizational *becoming* stance (Tsoukas & Chia, 2002) as the ontological perspective rather than the organizational *being* stance, which relies on a certain stability of organizational behavior and exists independent of the observer (Tsoukas, 2017).

Additionally, the observed phenomenon strongly depends on its context, which may include the world economy and the organization's financial situation, product portfolio, resource availability and competitors' moves. Because of this context dependence, it is not possible to perform precise generalizations concerning the dynamics of rework; rather, it is necessary to understand the context and the different perspectives of the main stakeholders (Wells & Smyth, 2015). For this reason, the epistemological stance, which concerns the nature of the knowledge being produced, adopted by this study is interpretivism; this perspective is suitable for this study owing to the complex environment of a product development project (Biedenbach, 2015).

Based on the framework presented by Kilduff, Mehra, and Dunn (2011), this research is positioned in the instrumentalist organizing philosophy and the problem-resolving logic. Considering the ontological stance, it does not aim to represent reality because the reality is changing constantly, and considering the epistemological stance, there is no purpose of obtaining a definitive truth because the phenomenon needs to be understood, based on its context and its stakeholders, by means of interpretation.

The research approach adopted is inductive. This approach involves exploring underdeveloped constructs or cases in which complex observation is required (Love, Mandal, et al., 1999). As a result, the identification of patterns and development of theories can be achieved (Bosch-Rekveldt, 2015). This is in accordance with the present research, which recognizes the dynamics of rework as complex and considers the identification of patterns as a way to address the negative impacts of EDR.

3.2 RESEARCH DESIGN

This research adopts the qualitative methodology, which is in alignment with the research organizational ontological-epistemological stances of *becoming* and interpretivism and the inductive approach. From the research philosophy point of view, the qualitative research design is appropriate because the researcher needs to comprehend the social constructs of a *becoming* reality. On the other hand, from the inductive approach point of view, the research design is emergent; it looks forward to develop an enriched conceptual framework (Saunders et al., 2012).

The qualitative research strategy for this study is the case study. This strategy is preferable for three main reasons.

First, management situations can be studied as complex systems due to the interdependence and interconnection between actors, elements and context (Bredillet, 2016). According to Aaltio and Heilmann (2010), the case study is common in a causal research setting because it is suitable for identifying the variables involved in managerial problems as well as identifying the relations between those variables; thus, this approach is aligned with the research question and research objectives of this study.

Second, case study research seeks to explain and understand individual cases in their own contexts (Aaltio & Heilmann, 2010), which is suitable for this study because the phenomenon of interest, the dynamics of rework, is embedded in the product development project context.

Third, initial paths of generalization are expected to be achieved, once variables and feedback loop relationships of the dynamics of rework are identified within a particular context (Aaltio & Heilmann, 2010; Love et al., 2016). Even though, there is debate concerning the generalizability of case study research (Flyvbjerg, 2016), the case study is considered an appropriated starting point for the process of knowledge accumulation that can lead to future theories on the dynamics of rework within product development projects.

R. K. Yin (2003) classified case study designs into four types: holistic single case, holistic multiple case, embedded single case and embedded multiple case. This research used the holistic single case, as justified below.

3.2.1 Single case study

There are three main reasons presented here to justify why this research has chosen a single case study. They concern the case study revelatory aspect, time horizon and representativeness (Saunders et al., 2012, p. 179; R. K. Yin, 2003, pp. 40-42).

Concerning the revelatory aspect the single case study is appropriate (R. K. Yin, 2003) because, as revealed in the literature review analysis from chapter 2, no studies about the dynamics of rework were found in the product development literature. Thus, the single case study can contribute to filling this literature gap.

The time horizon for this research is longitudinal (Saunders et al., 2012; R. K. Yin, 2003) rather than cross-sectional because the dynamics of rework can be presented at different points in the life cycle of a complex product development project, one of which is the single case study of interest.

Finally, concerning the representativeness of a single case study (R. K. Yin, 2003), in the preliminary phase of this research, the presence of the EDR in product development projects was validated as a real managerial problem by seven practitioners within the aerospace industry (Table 1.6) from different countries. Thus, the single case study provides lessons to improve the performance of other complex product development projects.

3.2.2 Unit of analysis

The single case study of this research is based on a single unit of analysis, which seeks to understand the dynamics of rework from a holistic perspective (R. K. Yin, 2003). The case study will be analyzed from a holistic perspective in order to achieve the main objective of this research, which is to better understand the dynamics of rework. Additionally, the research subobjectives require identifying the variables presented in the preliminary conceptual framework as well as the relationship among them.

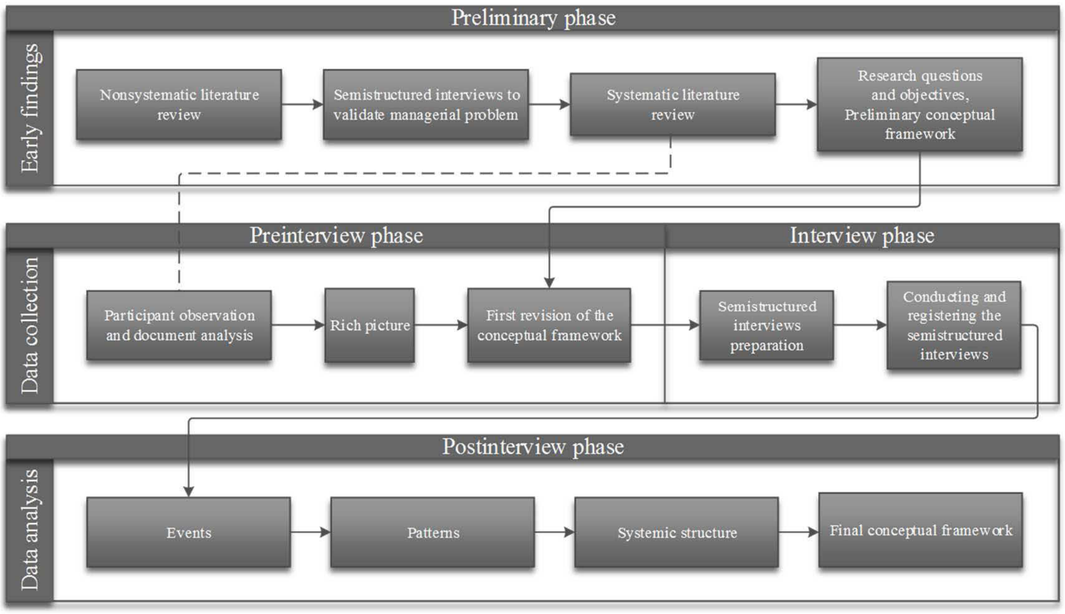
3.3 SAMPLING STRATEGY AND PURPOSEFUL SELECTION

The case study selected for this research should correspond to a complex product development project in which the researcher has access to multiple data sources related to the project in order to understand the organizational and product development context, answer the research question and achieve the research objectives, which involve identifying the dynamics of rework in a complex product development project by identifying the main variables and their relationships.

3.4 RESEARCH METHODOLOGICAL STRUCTURE

As discussed, this research follows an inductive approach, and the qualitative research strategy is the case study. The objective of the data collection and analysis is to propose a revised final version of the preliminary conceptual framework presented in Figure 2.20. The overall research methodology is structured in four phases, as presented in Figure 3.1.

Figure 3.1
Research methodology process



(Melo, 2019)

The research preliminary phase concerns the early findings of this research, which were based on four main activities: the nonsystematic literature review, semistructured interviews to validate the managerial problem (§1.3.3), the systematic literature review

(§2.1) and the definition of the research question and objectives as well as the proposal of a preliminary conceptual framework (Figure 2.20).

The remaining three phases, which are the preinterview phase, the interview phase and the postinterview phase, comprise the strategy for the data collection and the data analysis, discussed in the following sections.

Taking into account the complexity of the problem being investigated, the dynamics of rework, the soft systems thinking methodology seems appropriate as the basis of the research data collection and analysis strategy. The soft systems thinking methodology is a holistic approach and has been an alternative to traditional project management to address the realities of complexity and changing environment in projects (Jackson, 2003). It supports the identification of the structures and patterns behind complex problems (Senge, 1994) so that high-leverage actions can be applied to produce the desired results (Arnold & Wade, 2015; Sterman, 2000).

Therefore, the soft systems thinking methodology is in alignment with the research question and objectives, the research methodological position and approach and the qualitative research design, which is the case study.

The strategy for data collection relies on three main data sources: participant observation, documentation analysis and semistructured interviews. The data collection process was divided into the preinterview phase and the interview phase. The details are discussed further in the following sections.

3.5 DATA COLLECTION – PREINTERVIEW PHASE

The preinterview phase comprises three main groups of activities. The first concerns the data collection through researcher participant observation and documentation analysis. The second group is related to the rich picture, which is a technique of systems thinking methodology. The third group that joins the preliminary conceptual framework and the rich picture, resulting in a first revision of the conceptual framework.

3.5.1 Participant observation and documentation analysis

In this group of activities, the data collection relies on the following qualitative techniques: participant observation and documentation analysis of the single case study.

Participant observation is one of the qualitative data collection methods used in this research. This method adds richness to the overall ensemble of data collected through the research process because the researcher is immersed in the fieldwork and is exposed to the organizational context, which expected to contribute to a better understanding of the meaning of the data collected (Saunders et al., 2012, p. 340). In the participant observation method, the research instrument is the researcher him- or herself. Thus, the researcher has the discretion to identify the events, facts, and discussions that are important information (R. K. Yin, 2016, pp. 108, 129). A notebook is used to capture the researcher's observations.

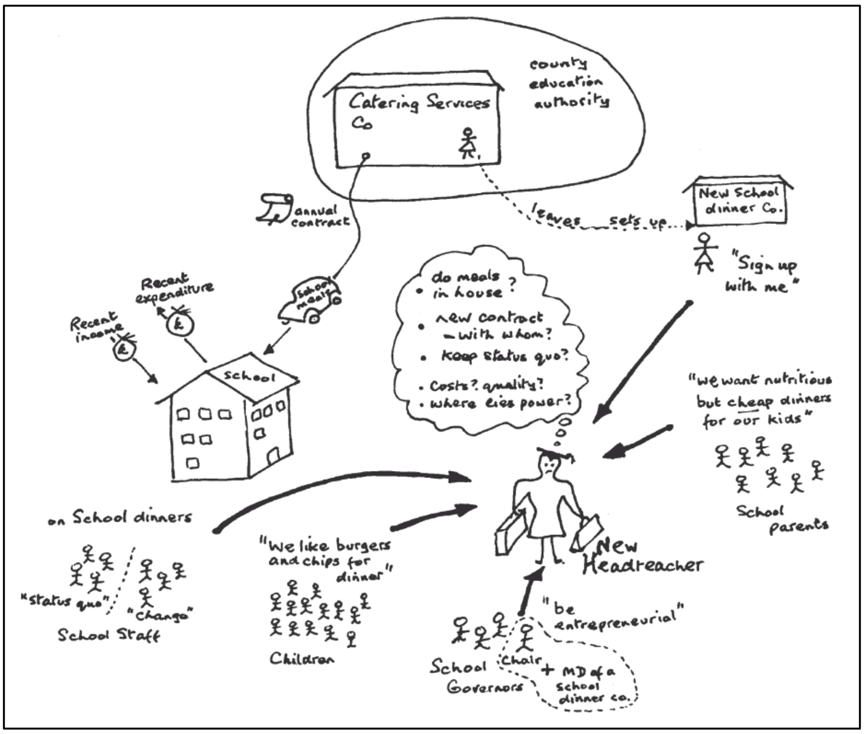
Documentation analysis represents data from secondary sources, meaning existing data of the case study that were previously collected for other purposes, not specifically for this research, but that can be used as a source of evidence for the case study (Saunders et al., 2012, p. 304). The sources of the data to be collected are the documents of the organization, such as internal communications, newsletters, written reports and previous project evaluations as well as archival records, such as organization charts and previous surveys; and project progress reports concerning cost, schedule and technical changes (R. K. Yin, 2003, p. 83).

3.5.2 Rich picture

The rich picture is a technique of the soft systems thinking methodology proposed by Peter Checkland (Checkland, 1985; Checkland & Poulter, 2010). One of its advantages is that the complex problem being investigated, as well as its environment, is represented in a single picture. The rich picture may capture stakeholders, processes, their relationships and facts relevant to the complex problem (Jackson, 2003). Figure 3.2 presents an example of a rich picture.

The rich picture is a live document obtained from the emergent research process. As more information becomes available, resulting from document analysis, discussions with professionals, workshops and interviews, the picture become more enriched, providing a holistic view of the complex problem (Checkland & Poulter, 2010).

Figure 3.2
Rich picture example



Source: (Checkland & Poulter, 2010)

Complex product development projects involve a large number of stakeholders and commercial and technical trade-offs owing to the intrinsic complexity of the product being developed. Thus, the rich picture is a useful means to depict the stakeholders' conflicting perspectives (Checkland & Poulter, 2010) on the dynamics of rework. It also provides a common understanding of the case study complexity, interdependencies and interconnectedness for the participants in the study (Strang & Masys, 2016).

The rich picture should be presented to the practitioners of the organization where the case study is being undertaken. This step is mandatory to provide the practitioners with feedback from the researcher's perception of the case study. The acceptance of the initial rich picture will give the researcher the necessary basis to integrate the preliminary conceptual framework (Figure 2.20) with the information identified from the case study to that point.

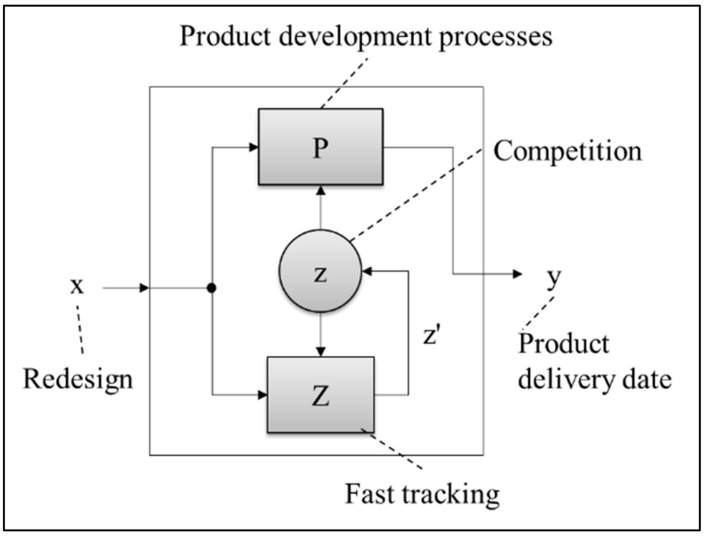
3.5.3 First revision of the conceptual framework

At this point of the methodology, the preliminary conceptual framework (Figure 2.20) and the initial rich picture of the case study will be integrated. This represents the first revision of the conceptual framework, which will again be revised in the postinterview phase and then will become the final conceptual framework version of this research.

The purpose is to identify the correspondence between the five elements of the preliminary conceptual framework (Figure 2.20) and the rich picture elements, such as the facts, managerial decisions, stakeholders and processes of the case study based on the researcher's initial assessment during the preinterview phase. Figure 3.3 presents an example of the integration of the preliminary conceptual framework and the rich picture.

Figure 3.3

First revision of the conceptual framework example



(Melo, 2019)

3.6 DATA COLLECTION – INTERVIEW PHASE

The interview phase comprises two main groups of activities. The first group concerns the semistructured interview preparation, and the second group concerns the activities needed to conduct and document the semistructured interviews.

3.6.1 Semistructured interview preparation

The semistructured interview is an essential data collection method in case study research (R. K. Yin, 2003, p. 89) and is the third data collection method used in this study. The number of interviews depends on the achievement of data saturation (Saunders et al., 2012, p. 283). Two important steps must be undertaken in the semistructured interview preparation: the selection of the interview candidates and the preparation of the interview guide, as discussed below.

Considering that thousands of people can be part of complex product development projects, the interviewee selection is an important step in this research methodology.

To interview the relevant project participants in a feasible time frame, three main criteria for the selection of interview candidates are defined. First, the candidates should still work in the organization; second, the hierarchical level of the candidates should be range from at least subject-matter expert (SME) to director; and third, the candidates who were part of the case study for a longer period are favored over those who participated for shorter period.

The final revision of the conceptual framework is performed after collecting the data through semistructured interviews. Based on the research question and objectives, this study seeks to identify the variables and the relations among the variables of the dynamics of rework. For this reason, the questions of the semistructured interviews should be fully justified and have a clear purpose and strong theoretical foundation.

The interview guide is divided into three parts. The first part inquires about the interviewee's cognitive map, that is, his or her perception of the case study. The second part inquires about the interviewee's perception of the holistic representation of the project illustrated by the rich picture. The third part inquires about specific issues identified in the participant observation. Table 3.1 presents the interview guide.

Table 3.1

Interview guide

First part – Interviewee's cognitive map
1) How do you summarize your experience in participating in the project? 2) What worked well? 3) Is there anything that did not really work? What were the most critical factors? 4) What is your recommendation for the next product development project?
Second part – Interviewee's perception of the holistic representation of the project (rich picture)
5) What was your first impression of the rich picture? 6) Did you recognize in the rich picture your interfaces during the program (process, teams, systems)? 7) What is your impression of the work execution (in terms of concurrency, schedule targets)? Do you believe it was beneficial/harmful for the program final results?
Third part – Specific issues from participant observation
8) From your point of view, what are the reasons for issues concerning requirement management (identification, validation, verification, traceability)? 9) Do you have examples of the impact of the requirements (speed, range, weight) on aircraft configuration, and vice versa? 10) How does it feel to work with evolving requirements/designs? What are your thoughts about the design change propagation in the project? Could it have been minimized?

(Melo, 2019)

To ensure the appropriate integration of the research objectives, the four themes identified in the literature review and the semistructured interview questions, in Table 3.2, the marks represent the relationships between the research objectives, the four themes of the literature review and the interview guide questions.

Table 3.2

Semistructured interview questions, research objectives and the literature review

Interview guide questions	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Research objective 1 – variables										
1.1 – Dynamics of rework triggers (x)	□				□					
1.2 – Product development project static factor (P)	□	□		□	□	□		□	□	
1.3 – Product development dynamic factor (z)	□				□		□	□	□	□
1.4 – Managerial decisions controlling factor (Z)	□	□	□	□	□			□	□	
1.5 – Product development project performance (y)	□	□	□	□	□			□		
Research objective 2 – variables relationships										
2.1 – x & P	□		□		□					
2.2 – x & Z	□		□		□					
2.3 – z & P	□				□				□	□
2.4 – z & Z	□				□				□	□
2.5 – P & y	□	□	□	□	□		□			□
Literature review – four themes										
Process architecture						□			□	□
Concurrency							□			
Project changing environment								□		□
System dynamics		□	□	□						□

(Melo, 2019)

3.6.2 Conducting and documenting the semistructured interviews

This step in the methodology explains how the semistructured interviews were conducted and how the information obtained in the semistructured interviews was captured.

However, before conducting the semistructured interviews, there is an additional step to be highlighted concerning the interview scheduling. First, this activity depends on the selection of the interviewee candidates. Second, authorization by the employee's supervisor for the employee to participate in the interview is required. Finally, scheduling also depends on employee's and researcher's availability.

Face-to-face semistructured interviews are expected to take place at the same site where the researcher is performing participant observation and at other sites of the organization. Phone calls are needed for interviewees located in other provinces and other countries.

The semistructured interview protocol starts with an introduction of the motivation and objectives of the case study and of the semistructured interviews followed by the semistructured interview questions. The interview closes with thanking the interviewee for participating. The expected duration of each semistructured interview meeting is approximately one hour.

Because the researcher was interviewing the organization's employees concerning a specific case study, due to confidentiality policies, recording the semistructured interviews was not authorized by the organization. For this reason, the information acquired during the interviews was captured only by means of note taking during the interviews, which is a standard practice for capturing data in qualitative research (R. K. Yin, 2016, p. 164). Moreover, the researcher has the support of two colleagues who also took notes in order to contribute to the production of reliable and complete data.

Another technique to avoid bias and assure data completeness and reliability is to revise and convert the notes in interview reports after each interview. The interview reports should include the interviewee's information, such as identification, role in the project, and background, and interview information, such as date, time and place the interview was conducted, and any additional information that may be useful for further analysis (Saunders et al., 2012, p. 394; R. K. Yin, 2016, p. 169). Annex B presents the interview report template.

The strategy for the data analysis relies on three main groups: a holistic understanding of the case study, the identification of behaviors' patterns and the proposition of the conceptual framework concerning the dynamics of rework. The data analysis process takes place in the postinterview phase. Further discussion is as follows.

3.7 DATA ANALYSIS – POSTINTERVIEW PHASE

The postinterview phase comprises the research data analysis. The activities of this phase are divided into three main groups and follow the iceberg model described in (Stroh, 2015, p. 37). The iceberg model allows the understanding of the dynamics of rework from three perspectives: *events*, *patterns* and *systemic structure*, as shown in Table 3.3.

The tip of the iceberg is the *events* layer. This includes the holistic understanding of the managerial problem context, the main facts, the involved stakeholders, the decisions made and the available options. The causal map and the rich picture are the techniques of soft systems thinking being used to depict the case study events gathered during the data collection.

The center of the iceberg is the *patterns* layer. It represents the perspective of a deeper understanding of the dynamics of rework because patterns of behaviors are being sought. For this reason, system archetypes are used because they are generic patterns of behaviors previously identified in the literature (Rehak, Lamoureux, & Bos, 2006).

The bottom of the iceberg is the *systemic structure* layer. This layer represents the mechanism that gives rise to the previous layers' results and it is the ultimate goal of this research. For this reason, a causal loop model is used to represent the systemic structure of the dynamics of rework and to review the final version of the conceptual framework of this study.

Table 3.3

Iceberg model and dynamics of rework data analysis

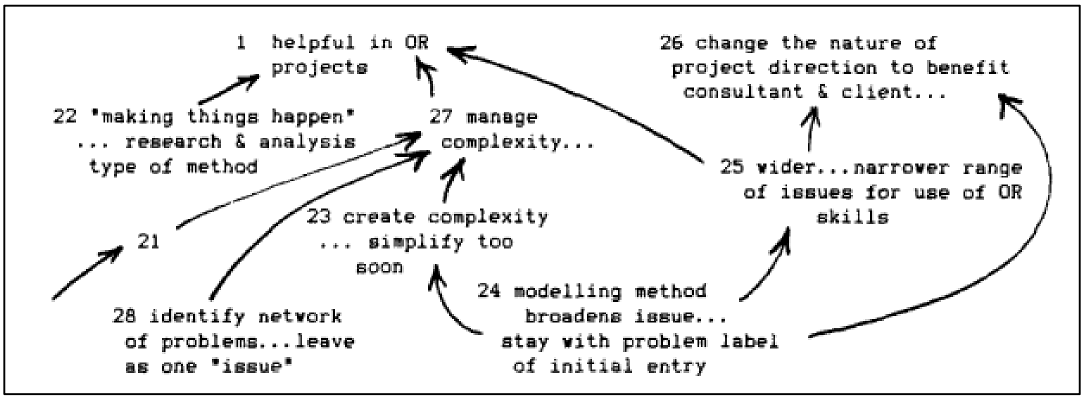
Iceberg layers		**Soft system thinking techniques**	**Case study**
	*Events*	Causal map and rich picture	History
	Patterns	Systems archetypes	Identified patterns of behavior
	Systemic structure	Causal loop model	Dynamics of rework

(Melo, 2019)

3.7.1 Events

Eden developed a method of organizational research for problem structuring using cognitive mapping. The method was based on Kelly's theory of the psychology of personal constructs (Eden, 1988). The idea is to make sense of organizational issues by capturing stakeholders' explanations. The cognitive map presents the causal relation of constructs connected by arrows. Causal maps are a result of merged cognitive maps from a variety of stakeholders (Eden, 1994). Figure 3.4 presents an example of a causal map.

Figure 3.4
Causal map example



Source: (Eden, 1988)

The causal maps can provide insights into the complexity of the organizational problem being investigated. They allow the understanding of circular structures between the chain of events rather than only linear cause-effect structures (Eden et al., 1992). This circular causality structure can assume two basic behaviors, either reinforcing or balancing feedback loops (Kim, 1993). Indeed, a single causal map may contain many loops. Thus, understanding and assessing the loops is pursued to understand the dynamic behavior of the problem being investigated.

In this research, the dynamics of rework, in complex product development projects, is the complex problem of interest. As a consequence, all the data collected in the previous phases support the creation of the causal map of this study. The software Decision Explorer (version 3.5.0) from Banxia Software is used as the tool to build the causal map.

Moreover, insights into the complexity of the causal maps can be provided by quantifying the number of arrows and constructs within the map. The higher the ratio of arrows and constructs, the higher the causal map complexity is. Another insight concerns constructs that are highly interconnected, i.e., constructs that send and receive many arrows. These constructs can represent local points of complexity in the map, for which further investigation may be recommended (Eden et al., 1992).

Thus, the causal maps are a useful technique to better understand the causes and consequences of major issues in the organization as well as in the projects despite not neglecting the context or the different stakeholder's views. As a consequence, the chain of causality represented in the causal maps provides a holistic view of the problem being assessed. An example of applying causal mapping to understand failure in complex projects can be found in Ackermann and Eden (2005).

The causal map technique is completely aligned with the case study methodology because the chain of causality is one of the possible proofs of reliability of the managerial problem being studied, which is the dynamics of rework.

3.7.2 Patterns

System archetypes are generic systemic structures comprising reinforcing and balancing feedback loops that give rise to complex organizational behavior patterns over time (Kim, 1993; Sterman, 2000). System archetypes are a tool of system dynamics methodology for qualitatively modeling feedback loops (Senge, 1994). Additionally, system archetypes have been identified in different domains and represent a common language to model and make sense of complex problems (Rehak et al., 2006).

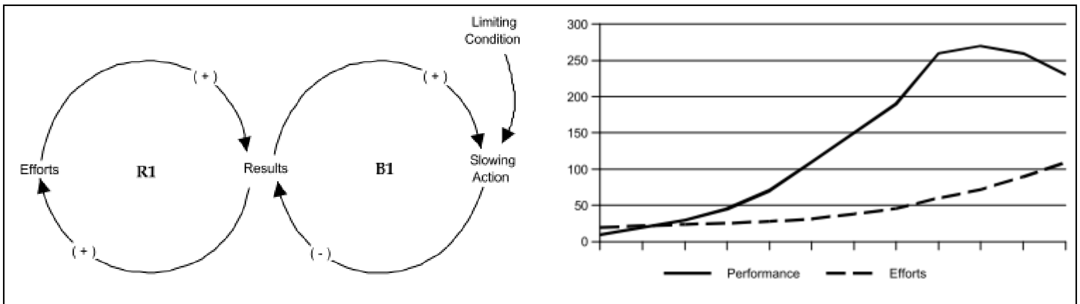
Examples of system archetypes are *limits to growth* (Meadows, Meadows, Randers, & Behrens, 1972), *eroding goals*, *shifting the burden*, *fixes that fail* and *tragedy of the commons* (Senge, 1994). Many examples of the use of system archetypes to model complex situations are available (Kim, 2000; Rehak et al., 2006; Senge, 1994; Stroh, 2015).

In addition to the identification of the generic systemic structure, intervention actions are proposed for each system archetype (Braun, 2002; Kim & Lannon, 2002). The objective of the intervention actions is to influence the systemic structures to make the system behave as desired. The intervention actions include changing an organization's policies (Sterman, 2000, p. 7), perceptions and mindsets (Senge, 1994).

Figure 3.5 presents an example of the system archetype *limits to growth*. The left side of the figure depicts the generic systemic structural model of the archetype, comprising a reinforcing loop (R1), a balancing loop (B1) and four generic variables connected by arrows. The right side of the figure shows the generic behavior of this archetype over time (Braun, 2002). The archetype illustrates situations in which initially, due to the reinforcing loop (R1), more efforts are made and more results are achieved. However, as time passes, due to the balancing loop (B1) and a limiting condition, the results will no longer increase, and can even decrease, independent of increasing the effort.

Figure 3.5

Systems archetype *limits to growth*



(a) Systemic structure (b) Behavior over time

Source: (Braun, 2002)

The generic recommendation for this archetype relies on understanding the reinforcing loop (R1), balancing loop (B1) and limiting condition in the context being investigated as well as understanding how the loops behave in the short- and long-term. Thus, slowing action and limiting condition can be anticipated and addressed before they start to influence the system negatively.

The objective of this step of the research methodology is to identify the system archetypes that may be presented in the case study causal map.

3.7.3 Systemic structure

This is the last step of the research methodology. The objective is to identify the main variables and the feedback relationships between the variables that represent the dynamics of rework and to propose a causal loop model. The system archetypes identified in the previous step are intended to support the representation of the dynamics of rework that is the basis for revising the conceptual framework and proposing its final version.

Therefore, understanding the systemic structures of the dynamic of rework may contribute to differentiation between the problem symptoms and problem causes, as well as better understanding the short- and long-term effects of project performance controlling actions. Therefore, high-leverage recommendations can be proposed in order to influence the systemic structure to improve the performance of complex product development projects by reducing the negative effects of EDR.

3.8 RESEARCH DESIGN QUALITY

Three tests are used to ensure the quality of the present research: construct validity, external validity and reliability (R. K. Yin, 2003).

3.8.1 Construct validity

There are three main tactics to ensure construct validity within data collection: the use of multiple sources of evidence, demonstration of a chain of evidence and validation of the collected data (R. K. Yin, 2003).

One of the multiple sources of evidence is the researcher's on-site participant observation. A second source is access to the documentation of the organization and the case study, for example, cost allocation, schedule execution, and change management documentation. A third source is the execution of interviews with participants relevant to the project at different hierarchical levels. These multiple sources of data collection allow data triangulation (Saunders et al., 2012).

The causal map technique supports the demonstration of the chain of evidence related to the studied problem. In addition, because as the causal map is a result of merged cognitive maps representing the different stakeholders' perspectives, it generates a richer and holistic understanding of the dynamics of rework within the complex product development project.

Finally, the interview guide was prepared to allow the assessment and revision of the preliminary conceptual framework (Figure 2.20) in accordance with the research question and research objectives. The questions in the interview guide are fully justified and have a clear purpose and strong theoretical foundation. The interview guide was reviewed by the researcher's professors and the practitioners in the organization. Moreover, the collected data were reviewed by relevant stakeholders in the organization, such as senior specialists and the interviewees.

3.8.2 External validity

External validity in single-case studies refers to the extent to which the study's results can be generalized to other case studies. However, case study research seeks analytical generalizations rather than the statistical generalizations that can be obtained through survey research, for example. In analytical generalizations, the purpose is to generalize a specific set of results to a broader theory (R. K. Yin, 2003).

The main goal of this research is to propose a conceptual framework representing the dynamics of rework in a complex product development project and this goal is expected to be achieved by identifying the main variables and the relationships among the variables through the identification of system archetypes, which are recognized as complex organizational behavior patterns. Therefore, the external validity of this research, its generalizability, relies on the identification of complex organizational patterns concerning the dynamics of rework that can be present in other complex product development projects.

3.8.3 Reliability

The reliability test ensures that the methodological steps for collecting and analyzing the research data can be replicated by other researchers. Another purpose of the reliability test is to mitigate the errors and bias of the researcher and the study participants (Saunders et al., 2012, p. 192; R. K. Yin, 2003, p. 37).

All the steps of this research methodology have been fully described in this chapter, from the methodological position and approach to the research design, including the systems thinking techniques used and the questions of the semistructured interviews. For the reasons presented previously, the research methodology transferability is believed to have been achieved by following the same steps as those used for the same case study.

3.9 RESEARCH ETHICAL ASPECTS

This research offers no risk or potential inconvenience to its participants. The format of the interventions, which were researcher participant observation, documentation analysis and semistructured interviews, was agreed upon between the researcher and the organization leaders.

The interview candidates were notified before the interview about the objectives and conditions of their participation in the research. They participated in the interview voluntarily. Additionally, they were notified that they could leave the interview at any time and without any penalty.

Finally, the confidentiality of any information concerning the participants, as well as the company, was assured. Additionally, no ethical certificate was needed to conduct this research, as letter of the UQTR ethics committee presented in Annex C.

3.10 METHODOLOGY SUMMARY

The research's methodological position, approach and design are summarized in Table 3.4.

Soft systems thinking methodology is the basis of the research data collection and data analysis strategy because it is a holistic approach that is suitable for the complexity and changing environment of projects (Jackson, 2003). It supports the identification of the structures and patterns that underlie complex problems (Senge, 1994) so that high-leverage actions can be applied to produce the desired results (Arnold & Wade, 2015; Sterman, 2000).

Table 3.4

Research methodological position, approach and design

Methodological position and approach	
Ontological stance	Becoming (Tsoukas & Chia, 2002)
Epistemological stance	Interpretivism (Biedenbach, 2015; Wells & Smyth, 2015)
Research philosophy	Instrumentalism (Kilduff et al., 2011)
Approach	Induction (Bosch-Rekveldt, 2015; Love, Mandal, et al., 1999)
Research design	
Methodological choice	Qualitative (Saunders et al., 2012)
Strategy	Holistic single-case study (R. K. Yin, 2003)
Time horizon	Longitudinal (Saunders et al., 2012)

(Melo, 2019)

The research phases and methodology steps are summarized in Table 3.5.

Table 3.5

Research methodology structure

Research phases	Research methodology steps
Preliminary phase Early findings	Nonsystematic literature review §1.3.3 Semistructured interviews to validate managerial problem §2.1 Systematic literature review §2.5 Research question and objectives, preliminary conceptual framework
Preinterview phase Data collection	§3.5.1 Participant observation and documentation analysis §3.5.2 Rich picture §3.5.3 First revision of the conceptual framework
Interview phase Data collection	§3.6.1 Semistructured interview preparation §3.6.2 Conducting and documenting the semistructured interviews
Postinterview phase Data analysis	§3.7.1 Events §3.7.2 Patterns §3.7.3 Systemic structure

(Melo, 2019)

CHAPTER 4 - RESULTS

The objective of this chapter is to present the research results. They are presented following the established strategy for data collection (§3.5 and §3.6) and data analysis (§3.7), as depicted in Figure 3.1.

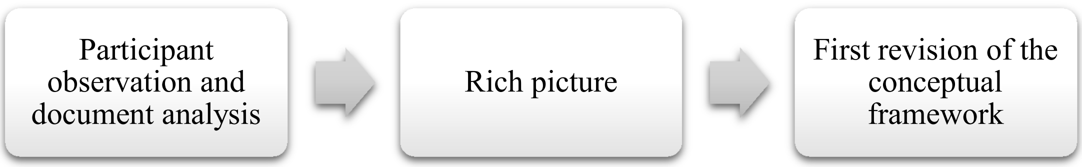
4.1 CASE STUDY DESCRIPTION

The case study took place in a Canadian OEM, a global industry leader and one of the world's top 10 aerospace companies. The case study examines a multibillion-dollar aircraft development project, in this document the *project*. Its duration was approximately 10 years, and it involved hundreds of suppliers and thousands of professionals. The product being developed was highly complex in terms of the level of development effort, the coordination between stakeholders and the overall project scope and budget. It introduced complex technologies that were new to this OEM as well as some first-to-market features. The scope of the project analyzed in this research is the project nonrecurrent development efforts.

4.2 DATA COLLECTION – PREINTERVIEW PHASE

The preinterview phase followed the three main steps presented in Figure 4.1.

Figure 4.1
Preinterview phase steps



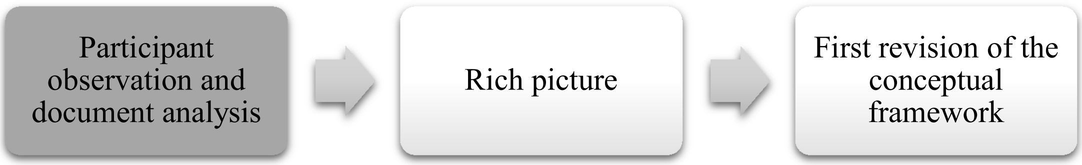
(Melo, 2019)

The first step is collecting the data by means of participant observation and documentation analysis. The second step is the creation of the first version of the rich picture. The third step is the first revision of the conceptual framework.

4.2.1 Participant observation and documentation analysis

Participant observation and documentation analysis are the first steps of the preinterview phase, as shown in Figure 4.2.

Figure 4.2
Preinterview phase, participant observation and documentation analysis step



(Melo, 2019)

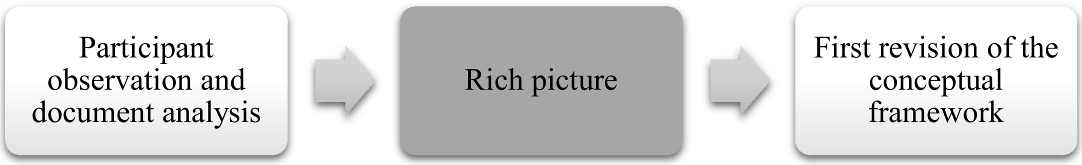
Participant observation started in the last year of the project. It included 12 ad hoc meetings with professionals who had different perspectives on the project owing to their roles in finance, project management, product development, information technology, change management, configuration management, requirement management and integration management. The professionals included senior engineers, conceptual designers, project managers and project directors. The participant observation contributed to learning about the project context and preliminary phases.

The documentation analysis included hundreds of documents including previous assessments of other product development projects undertaken by the organization, organizational procedures, assessments of the project initial phases, project costs, the project schedule and technical change requests. The documentation analysis helped the researcher understand the sources of project nonrecurrent expenses, the actual dates when project milestones were achieved, the categories of the major EDR, the technical teams that were impacted and/or impacted other teams due to technical changes, the suppliers involved in the project and the different global locations where the project was undertaken.

4.2.2 Rich picture – first version

The rich picture is the second step of the preinterview phase, as shown in Figure 4.3.

Figure 4.3
Preinterview phase, rich picture step



(Melo, 2019)

The great benefit of creating the rich picture is to illustrate, on a single page, the processes, the stakeholders, their relationships and a summary of the main facts of the complex problem being investigated. The first version of the rich picture, Figure 4.4, was created based on the participant observation and documentation analysis and is described as follows.

Owing to the combination of a competitive market environment, the concurrent development of other products and the fact that the organization's experts were occupied, the decision was to propose a product solution that could reach the market quickly. As the product development progressed, the product was found to lack certain capabilities, and the decision to add them to the project scope was made, leading to EDR activities.

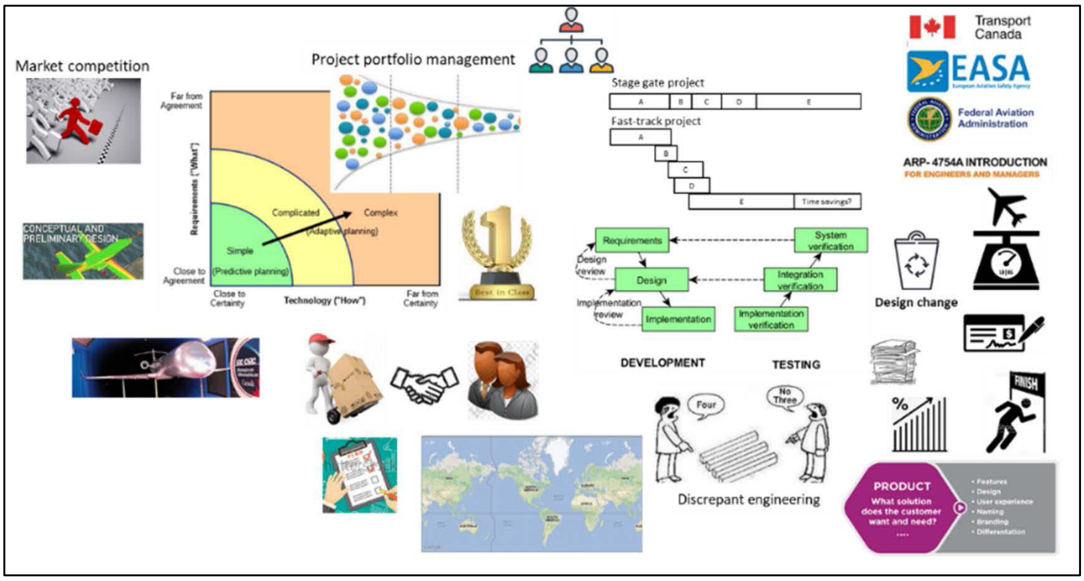
As the organization’s experts were occupied with other product development projects, this contributed to a product definition that did not perform as desired, which in turn led to further EDR activities.

EDR activities also impacted the suppliers because they increased the level of effort and complexity as well as the agreed-upon working hours, which in turn led to commercial disputes. The combination of EDR activities and commercial disputes with the suppliers led to additional costs and delays, negatively impacting the project performance in terms of time and cost. However, EDR activities enabled the development of an outstanding product that was ahead of the competition.

The first version of the rich picture, presented in Figure 4.4, illustrates aspects of the organizational, project and product contexts that are highlighted in Table 4.1.

Figure 4.4

First version of the rich picture during the preinterview phase



(Melo, 2019)

Table 4.1

Highlights of the first version of the rich picture

Organizational context	Description
Market competition	The organization was not alone in the market; there were competitors Product solution should be quick to market
Organization's project portfolio management	Organization was managing other product development projects concurrently
Project context	
Expert availability	Experts were occupied with other projects during conceptual design phase
Project scope evolution	Evolved from simple to complex; consequently, project budget and schedule were underestimated
Multisite project	Project involved different sites
Contracting suppliers	Hundreds of suppliers
Product development process	Staged gate/quality gates
ARP-4754A standards	System engineering V-model standards to be followed
TCCA, EASA and FAA	Regulatory agencies
Fast-track product development phases	Decision to overlap product development phases to accelerate project progress
Design changes, discrepant engineering	Product scope evolution, experts not available in conceptual design phase
Commercial disputes	Suppliers considered design changes as out-of-scope activities
Additional project costs and lateness	Design changes, commercial disputes
Product context	
Product scope	Evolved from simple to complex
Product weight	Should be reduced
Delivered product, best in class	Outstanding, ahead of the competition, potential first option for customers

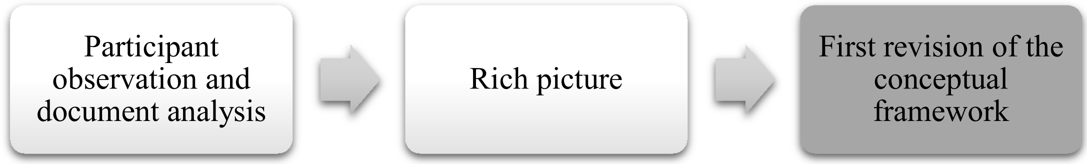
(Melo, 2019)

4.2.3 First revision of the conceptual framework

The first revision of the conceptual framework, which is the merging of the preliminary conceptual framework (Figure 2.20) with the rich picture elements (Figure 4.4), is the third step of the preinterview phase, as shown in Figure 4.5.

Figure 4.5

Preinterview phase, first revision of the conceptual framework step



(Melo, 2019)

The correspondence between the conceptual framework elements and the rich picture is summarized in Table 4.2.

Table 4.2

First revision of the conceptual framework

Conceptual framework elements		**Rich picture elements**
x	Triggers of the dynamics of EDR	Design changes, discrepant engineering
P	Product development project static factors	Product development process, ARP-4754A standards
z	Product development project dynamic factors	Market competition, expert availability, increased product complexity, commercial disputes
Z	Product development project performance controlling factors	Fast-track product development phases, organization's project portfolio management, contracting suppliers, project scope evolution
y	Product development project performance	Additional project costs and lateness, product delivery, product scope, product weight

(Melo, 2019)

The data collected during the preinterview phase through participant observation and documentation analysis, as well as the creation of the first version of the rich picture, were important for understanding the big picture of the complex problem being investigated and for allowing the researcher to proceed to the next phase proposed in the methodology, which is the interview phase.

4.3 DATA COLLECTION – INTERVIEW PHASE

The interview phase followed the two main steps presented in Figure 4.6.

Figure 4.6
Interview phase steps

(Melo, 2019)

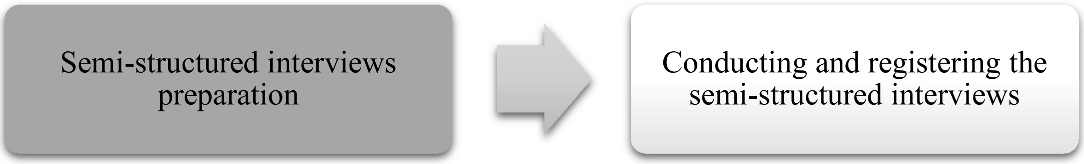
In the first step, information related to the total number of semistructured interviews conducted, the interviewees' hierarchical level and their experience with the project is presented. In the second step, information regarding the location where the interviews took place and the duration of each interview is presented. The information collected in this phase enabled the researcher to proceed to the postinterview phase, which is the research data analysis.

4.3.1 Semistructured interview preparation – results

The interview preparation is the first step of the interview phase, as shown in Figure 4.7.

According to the organization experts about two thousand people were part of the project. The suppliers' supply chain was not included in this estimate, meaning that this number could have been drastically higher. For this reason, the researcher was supported by senior leaders of the organization during the interviewee selection process.

Figure 4.7
Interview phase and interview preparation results step



(Melo, 2019)

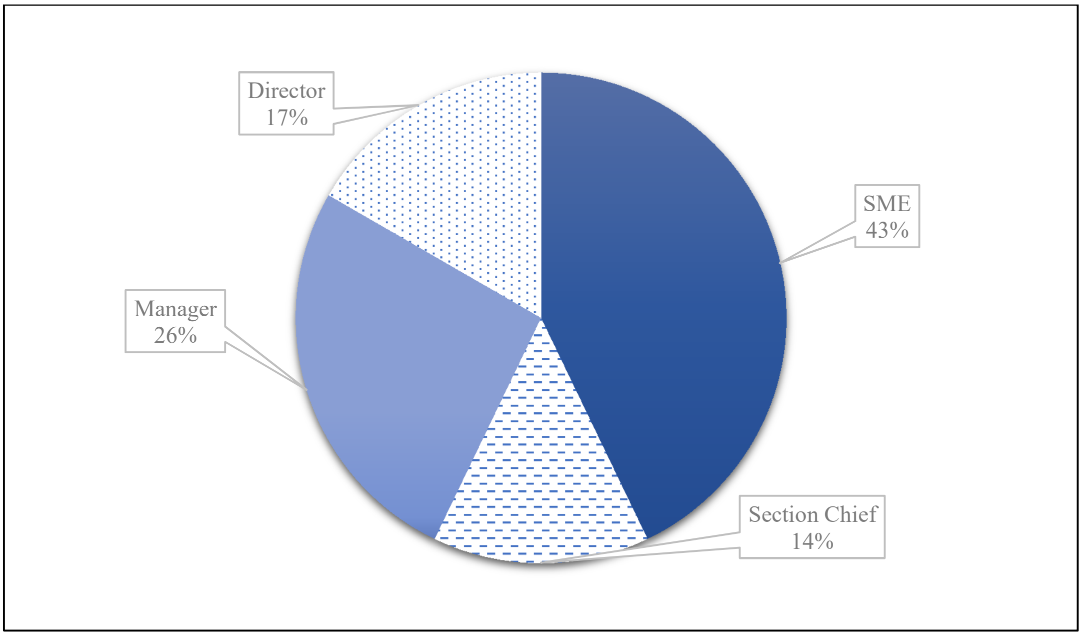
In addition to the ad hoc meetings in the preinterview phase, the researcher conducted 42 semistructured interviews to achieve information saturation. The interviewee selection was based mainly on the interviewees' hierarchical level and experience with the project.

Figure 4.8 presents the distribution of the interviewees' hierarchical level, with 43 % being subject-matter experts (SMEs), 26 % managers, 17 % directors and 14 % section chiefs. This distribution favored a vertical perspective contribution from the interviewees. In other words, among the interviewees, 43 % were professionals who executed the product development activities, and 57 % were professionals at leadership levels, that is, section chiefs, managers or directors.

Another aspect of the candidate selection was their experience with the project, which averaged six years. Figure 4.9 presents how long 38 of the interviewees were involved in the project – information for four interviewees is missing. Thus, 39 % of the interviewees were involved in the project from 5 to 7.5 years, 34 % were involved from 7.5 to 10 years, 21 % were involved from 2.5 to 5 years and 5 % were involved in the project less than 2.5 years. Considering that the project duration was approximately 10 years, nearly 73 % of the interviewees participated in more than 50 % of the total project duration, which is strongly significant.

Figure 4.8

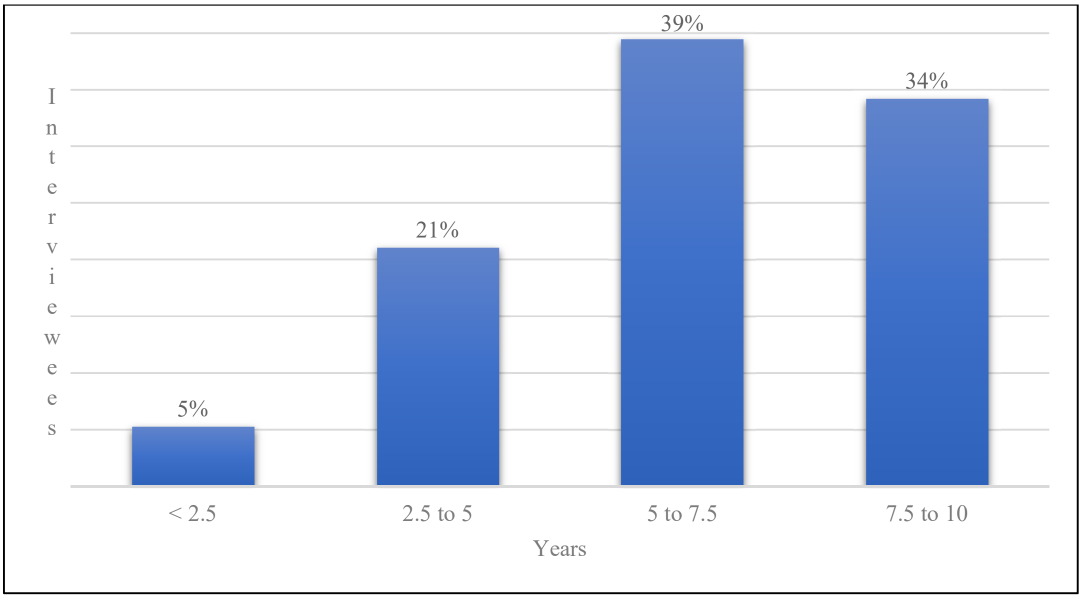
Hierarchical-level distribution of the interviewees



(Melo, 2019)

Figure 4.9

Interviewee experience with the project in years



(Melo, 2019)

4.3.2 Conducting and documenting the semistructured interviews – results

Conducting and documenting the semistructured interviews is the second step of the interview phase, as shown in Figure 4.10.

Figure 4.10
Interview phase, conducting and registering the semistructured results step

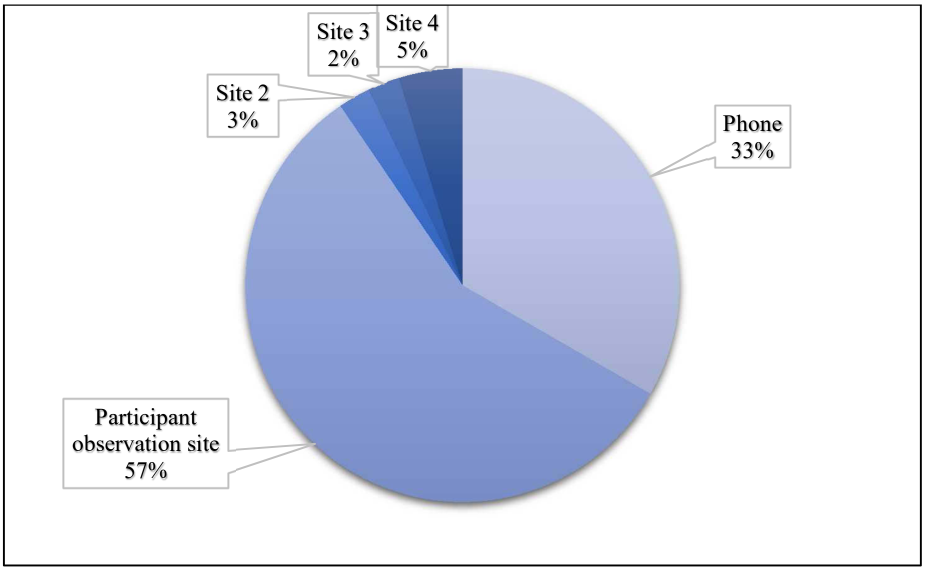
(Melo, 2019)

This section presents where the semistructured interviews took place, how the interviews were conducted, the interviews duration and how the interview notes were taken.

The semistructured interviews were conducted face-to-face in different locations, and some interviews were conducted by phone. Figure 4.11 presents the interview location distribution. Thus, 57 % of the interviews were conducted at the same site where the researcher was performing participant observation, 10 % of the interviews were at other sites within a 50-km radius from the participant observation site and 33 % of the interviews were conducted by phone, supported by display sharing. The participants interviewed by phone were in other provinces within the same country and in other countries.

Figure 4.11

Location distribution of the interviews



(Melo, 2019)

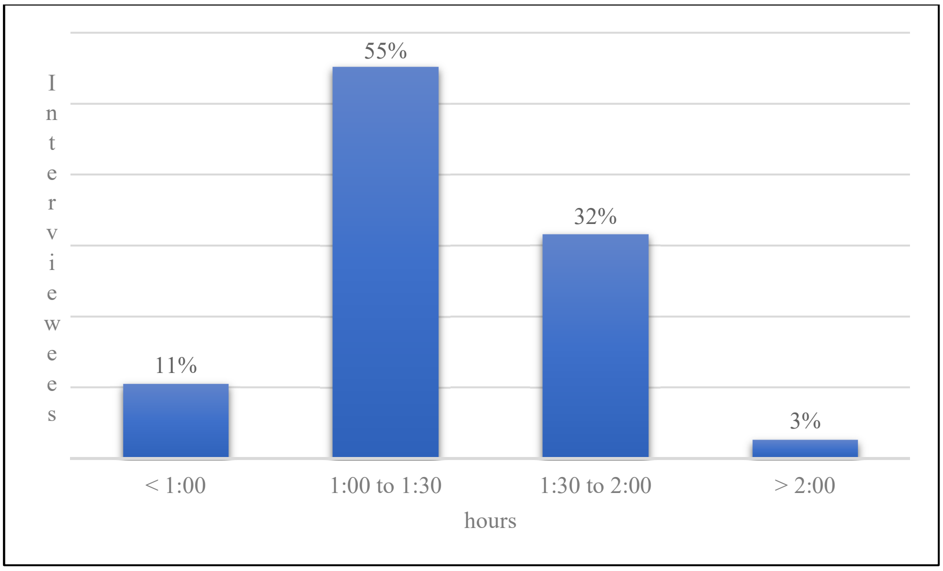
The interviews were conducted following the protocol presented in §3.6.2. They began with a brief introduction of the motivation and objectives of the case study as well as how the semistructured interview was organized. Immediately after the introduction, the chronometer and the interview were started.

As presented in Table 3.1, the semistructured interviews comprised three main parts: first, the interviewee's cognitive perception of the project; second, the interviewee's perception of the holistic representation of the project, supported by the rich picture; and third, specific issues identified by the participant observation during the preinterview phase.

At the end of the interviews, the participants were asked if they had any additional information they wanted to share and if they had any recommendations regarding the interview protocol. After the interview ended, the chronometer was stopped, and the participants were thanked for their time and generosity in sharing their experience.

The researcher had the opportunity to spend more than fifty hours with the interviewees over two months. The interview duration averaged one hour twenty minutes, with two interviews that lasted less than one hour and one that lasted more than two hours. Figure 4.12 presents the interview duration distribution among the interviewees; 55 % of the interviews were between one hour and one and a half hours, 32 % were between one hour and a half and two hours, 11 % were less than one hour and 3 % were above two hours.

Figure 4.12
Interview duration distribution among the interviewees in hours



(Melo, 2019)

The researcher did not have authorization from the company to record the interviews. Consequently, the information acquired during the interviews was captured by means of notes. The researcher was supported by at least one colleague and in several interviews by two colleagues. For confidentiality reasons, the interview notes are not presented in the thesis.

The information summarized in Figure 4.8 to Figure 4.12 indicates that the interviewee sample contributed to the holistic perspective sought for this study to understand the dynamics of rework in a product development project.

The rich picture was used during the second part of the semistructured interviews, and it was appreciated by the majority of the interviewees. It was an effective tool to trigger their memory and enable them to recall other facts and events of the project that helped the researcher make links between the process, teams and system interdependencies.

Cognitive maps were created for most of the semistructured interviews. The cognitive maps represented the causal relation between the events of the case study from the perspective of the interviewees. The information gathered during the interviews was used to create the causal maps in the postinterview phase, which was the next phase of the research.

The interviewees' willingness and openness to share their experience with the project during the interviews was a testament to their desire to seek improvements for future product development projects as well as the performance of such products. They were engaged in collaborating with the study as key active contributors of the organization.

4.4 DATA ANALYSIS – POSTINTERVIEW PHASE

The postinterview phase followed the three main steps presented in Figure 4.13.

Figure 4.13

Postinterview phase steps

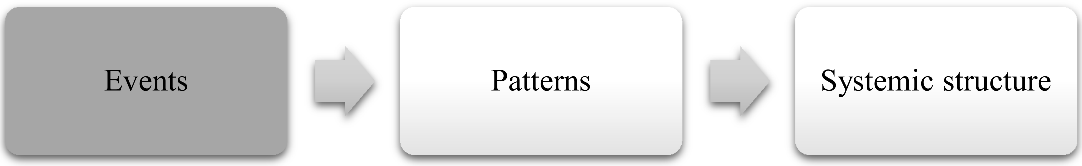
(Melo, 2019)

The first step presents and discusses the case study causal map and the final version of the rich picture. The second step presents the system archetypes identified in the causal map and rich picture. The third step presents the final version of the conceptual framework of the dynamics of rework.

4.4.1 Events

The causal map and the final version of the rich picture are the first steps of the postinterview phase, as shown in Figure 4.14.

Figure 4.14
Postinterview phase, events step



(Melo, 2019)

4.4.1.1 Causal map

One of the purposes of creating the causal maps was to make sense of the chain of causality of the complex problem being investigated. The maps are used to understand the causes and the short- and long-term effects of the decisions that were made throughout the product development as well as the available options and their consequences. An additional advantage of creating the causal map is that this technique does not neglect the context or the different stakeholders' perspectives. In addition, it is a good way to holistically communicate the problem being assessed by means of a chain of causality.

In this step of the research methodology, the data collection phase was finalized. The objective was to create a single causal map that incorporated the data collected from the participant observation and documentation analysis as well as the cognitive maps created from the semistructured interviews. The software Decision Explorer (version 3.5.0) from Banxia Software was used as the tool to build the single causal map.

The causal map comprises 187 concepts, with 41 heads and 25 tails. The concepts were connected with 146 links. In addition, 15 main concept clusters were identified. The ratio between the number of links and concepts was equal to 0.78, suggesting that the causal map had a moderate to high level of complexity. Table 4.3 summarizes the causal map numbers.

For confidentiality reasons the original causal map cannot be presented in the thesis. However, a public version of the original causal map was created and is presented in Figure 4.15. The causal map should be read from the bottom up, and the chain of events is described as follows.

Table 4.3

Causal map numbers

Concepts	187
Heads	41
Tails	25
Links	146
Clusters	15
Ratio of links/concepts	0,78

(Melo, 2019)

The product development project being investigated in this research was initiated in a highly competitive market context. At the same time, the organization was undertaking the development of other complex products that also required the time of the scarce product development experts. The organizational context limited the availability of the experts, the budget and the schedule for the studied product development project.

Consequently, the organization decided to develop a quick-to-market product solution based on a previous product version. This decision was made because the organization was assured that the product to be developed was well known and that it would have fewer technical challenges. This environment favored the mindset that the product development project scope was well understood. In addition, it contributed to the progress of the product development project with the available technical resources rather than needing the product development experts.

The product development project was undertaken in an expedited mode due to the reasons presented above: tight schedule and the mindset of a good understanding of the product development project scope. However, because of the competitive market environment, the organization decided to add capabilities to the product that increased its complexity and initiated a series of EDR activities.

Because of the tight schedule and the decision to expedite some project activities owing to the long lead time needed to manufacture parts, the engineering designs were neither mature enough nor optimal. Moreover, due to the capabilities added to the product, the conceptual design took more time to become stable and to meet all the product performance requirements. This delay resulted in overlap between the project phases, meaning that the product development teams were progressing concurrently but at different maturity levels. Additionally, due to the tight schedule, expedited activities and design changes made following the product development process impractical, thus contributing more disruption to project execution.

During the product development process, as more information was acquired, many of the designs that were considered well understood and suitable for reuse turned out to require new design development, which increased the product development complexity, resulting in EDR, more overall work, more costs and more delays.

Suppliers were contracted with a statement of work that significantly increased throughout the product design evolution. The added work increased the suppliers' level of effort and reduced their profit. Consequently, the collaboration between the organization and the supplier eroded, leading to commercial disputes. This in turn slowed the product development progress and contributed to the project delays.

It was revealed that the more advanced the product development project was, the more design changes became necessary, due mainly to the change propagation effect, which increased the amount of work to be done. This situation contributed to a high level of asynchronous work execution among the technical teams, leading to more changes and more overall work. Additionally, at a certain stage of the product development, the collaboration among the technical teams decreased because as the teams had more work to do, they worked more in isolation and performed less integrated work, which led to more problems arising and more EDR.

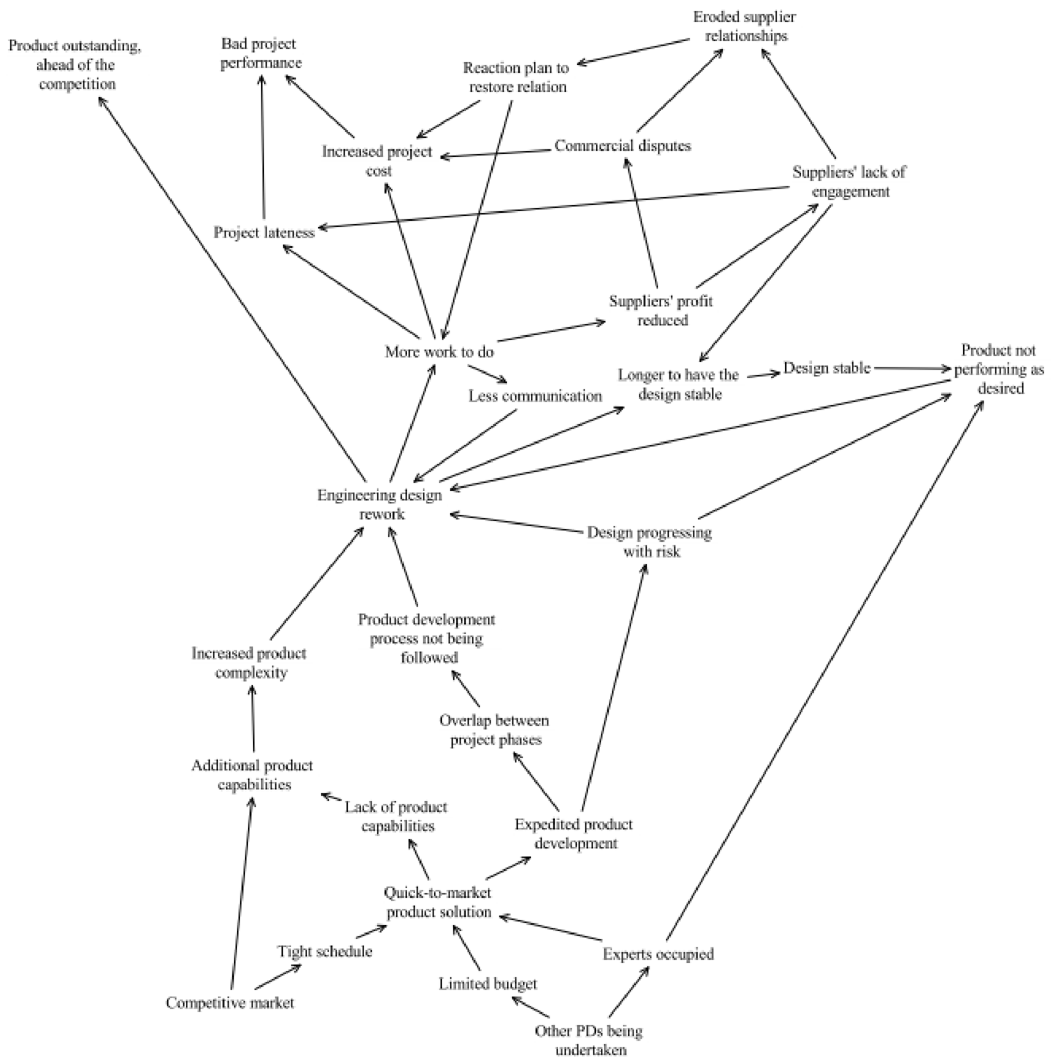
By the time the product design became stable, the other development programs had terminated or were ramping down, which freed the product development experts. Additionally, at that point of the product development project, the product performance was not satisfactory. Contributing factors revealed in the chain of causality were that the product development experts were not available in the preliminary phases of the project, and the technical teams were not given the appropriate time to reduce the technical uncertainties, which contributed to the proposal of non-optimal designs with excessive contingent margins (as a mitigating action to protect against the technical uncertainties). Consequently, the design needed to be refined to satisfy the product target performance, which initiated new EDR cycles.

As mentioned previously, the eroded relationship with the suppliers had negative impacts on the product development project. For instance, the supplier disengagement and the lack of collaboration impacted the product development progress as well as the designs being developed by the suppliers. Additionally, the organization needed to create a reaction plan to restore the eroded relationship, which resulted in additional costs for the product development project, such as sending technical teams (several professionals) to supplier sites and settlement payments due to commercial disputes with suppliers.

At the end of the product development project, the delivered product was outstanding and ahead of its competitors. However, it cost more, demanded more effort than had been forecast and took more time than anticipated.

Figure 4.15

Case study's causal map



Note: causal map should be read from the bottom up; the arrows connect causes to consequences

(Melo, 2019)

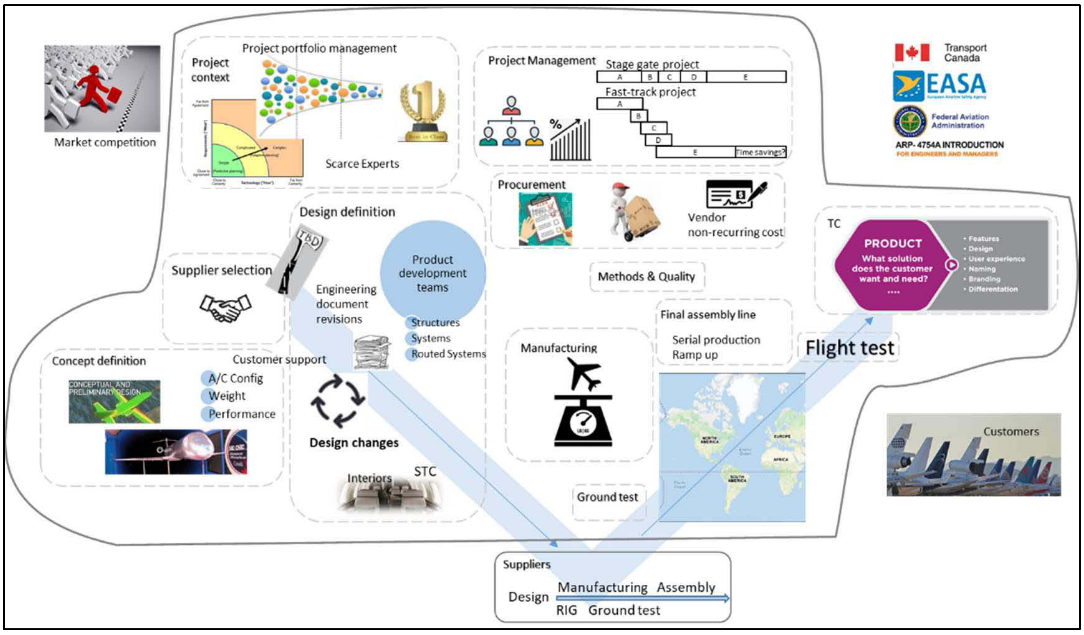
4.4.1.2 Rich picture – final version

As the rich picture is an emergent process, the first version presented in Figure 4.4 was enriched throughout the data collection phase, and the final version is presented in Figure 4.16.

In the final version of the rich picture, three main topics are highlighted. The first is the product development project main phases, such as concept definition, design definition, manufacturing, ground and flight test and final assembly. The second is the major stakeholders, such as competitors; customers; product development, customer support, methods, quality, and procurement teams; suppliers; project managers; and certification authorities. The third is the main contextual facts, such as market competitive environment, project portfolio management, design changes, vendor nonrecurring costs and the plurality of sites where the project was undertaken.

Figure 4.16

Final version of the rich picture postinterview phase

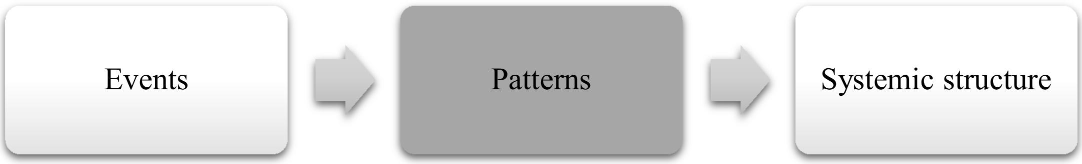


(Melo, 2019)

4.4.2 Patterns

The system archetypes identified in the causal map and rich picture are the second step of the postinterview phase, as shown in Figure 4.17.

Figure 4.17
Postinterview phase, patterns step



(Melo, 2019)

At this point of the data analysis, four models were built based on two system archetype structures identified in the data collected, in the causal map and in the final version of the rich picture.

4.4.2.1 Identified systems archetypes

Two main systems archetype structures were identified: "fixes that fail" and "shifting the burden". These system archetype structures were used as the basis of the four qualitative causal loop models proposed and discussed in the sequence.

4.4.2.1.1 "Fixes that fail" system archetype: reuse mindset

The organizational context was under pressure owing to a competitive environment and scarce experts. In such cases, a product solution should be proposed to address the competitor threat. The solution should fit within the budget, schedule and human resource availability constraints. The combination of the previous elements contributed to the organizational decision to propose a quick-to-market product solution based on a previous product version, i.e., a product solution that was familiar to the organization.

This decision was in alignment with the budget, schedule and human resource constraints of the company.

However, the competitive environment became even more challenging at the same time that the project was undertaken. The product solution that fit the budget and schedule was no longer sufficient to beat the competition. Therefore, additional product features needed to be added to the initial scope of the project, increasing the complexity of the product solution. This in turn initiated EDR cycles. The evolving understanding of the necessary effort to deliver a competitive product undermined the previously estimated budget and schedule that were authorized for the project.

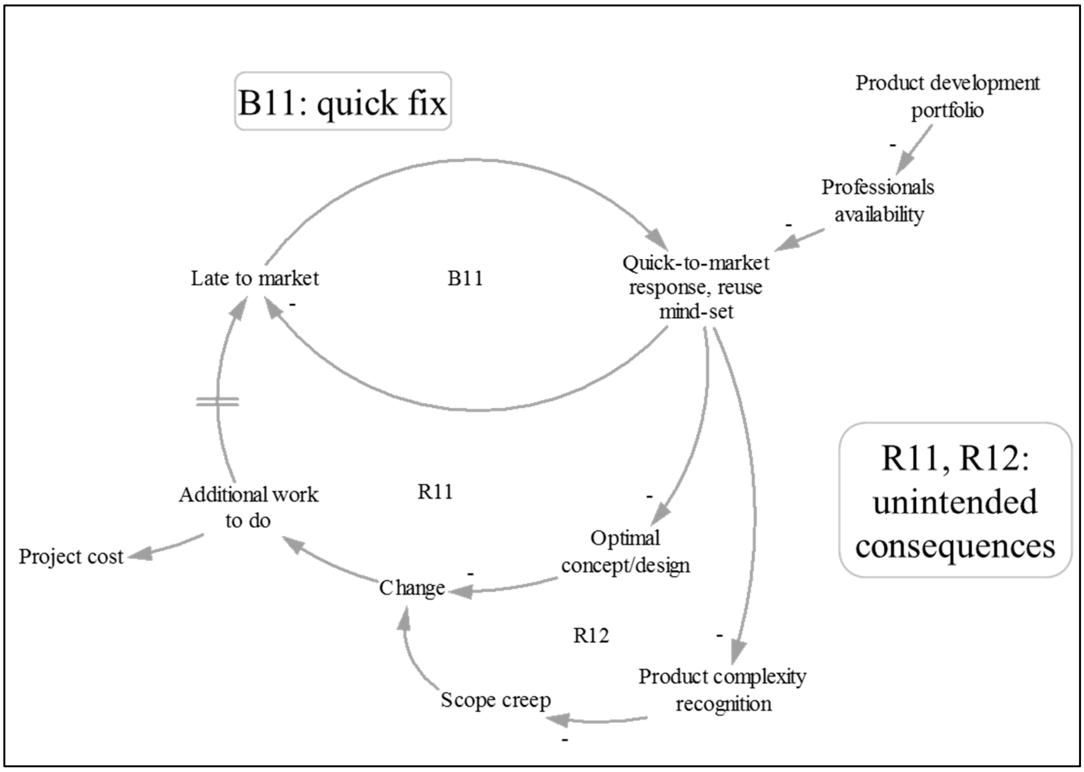
Modeling this event revealed that it matches the "fixes that fail" system archetype presented in Figure 4.18. The balancing loop (B11) connects the problem symptom variable and the quick-fix variable, which are the variables "late to market" and "quick-to-market response, reuse mindset", respectively. Therefore, to minimize the problem symptom, which is being late to market, the quick fix of delivering a new product based on a previous product version was implemented. The quick fix was reinforced by the product development portfolio of the company as well as the availability of the product development professionals. It was perceived as the right thing to do because the product solution was already understood by the organization, was supposed to consume less time and effort and consequently offered a reduced number of unknowns and uncertainties.

However, the quick fix resulted in unintended consequences that in the long term increased the problem symptom through the reinforcing loops (R11 and R12). Reinforcing loop R11 presents the unintended consequences of not achieving an optimal concept and/or design to the product, leading to the need for change, which consequently increases the amount of work to be done and contributes to delaying the product delivery and increasing the product development cost.

Additionally, a second unintended consequence is presented by reinforcing loop R12. Because the quick fix was anchored in a quick-to-market response and in a reuse mindset, it led to a lack of recognition of the product complexity, which in turn led to scope creep. The need to change, additional work and increased project cost undermining the goal of not being late to market.

Figure 4.18

Fixes that fail, reuse mindset



(Melo, 2019)

The recommendations to avoid the unintended consequences resulting from the underestimated project scope are to ensure that expert professionals are available up-front, perform a robust requirement management process and challenge the reuse of previous product development information. Expert professionals, based on their experience, can anticipate known unknowns and unknown unknowns. The requirement management process ensures the timely identification and validation of the product requirements in the initial phases of the complex product development project, which is essential for uncovering known unknowns and unknown unknowns. Finally, even though the reuse of previous product development information is an ideal start point, the information must be challenged for the new project, meaning that the information must be reassessed to determine whether it is appropriate in the new project context.

4.4.2.1.2 "Shifting the burden" system archetype: phase overlap

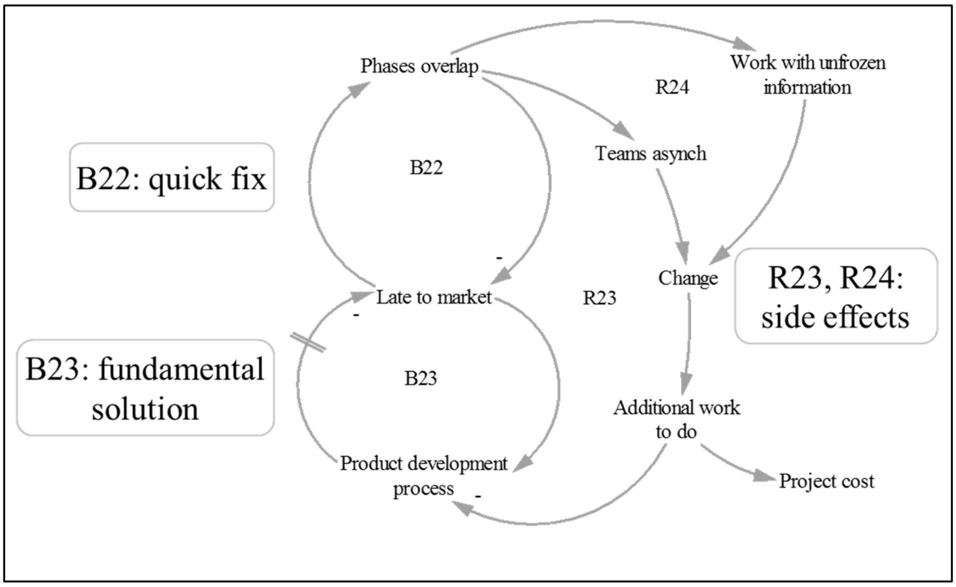
The organization was late to market, though it had already decided to propose a quick-to-market product solution based on a previous product version; in addition, the product development experts were not available. The combination of the earlier facts contributed to executing the product development project phases at high level of concurrence rather than sequentially, as expected in a product development process.

The concurrence of the phases forced the teams to work with unfrozen or outdated information, necessitating future changes and EDR activities. Additionally, some long-lead-times items were expedited, which led to asynchronous work execution between interdependent teams, which also unfolded into changes. The changes increased the amount of work necessary to accomplish the project. In such cases, it may become impractical to follow the optimal product development process due to disruptions caused by the need to rework.

Modeling this event revealed that it matches the "shifting the burden" system archetype presented in Figure 4.19. The balancing loop (B22) connects the problem symptom variable and the quick-fix variable, which are the variables "late to market" and "phases overlap", respectively. To minimize the problem symptom, being late to market, a quick fix was implemented. The quick fix was to overlap the execution of the product development phases to reduce the product development cycle. Initially, the quick fix seemed inoffensive and the best option for fast-tracking the project. However, the balancing loop (B23) shows the fundamental solution is to follow the product development process, i.e., undertake the product development main phases sequentially.

In addition, the quick fix triggered side effects that made the fundamental solution even more difficult to implement. The side effects are represented by the reinforcing loops (R23 and R24). Reinforcing loop R23 shows that the side effects of overlapping the product development phases led the teams to work asynchronously, i.e., not in an optimal activity execution sequence. This in turn resulted in changes and additional work to be done, which disrupted the product development process. Reinforcing loop R24 shows that overlapping the product development phases led the teams to work with unfrozen information, consequently leading to change and additional work to do, increasing the project cost and disrupting the product development process.

Figure 4.19
Shifting the burden, phase overlap



(Melo, 2019)

The first recommendation is to avoid high overlap of project phases. This recommendation becomes more important in the preliminary phases of a project. In the preliminary phases, the level of uncertainty is high, so the risk of reworking is also high; if reworking turn out to be necessary, it will disrupt the product development process. The second recommendation is to identify, before the execution phase, the optimal development activities sequence, that allows the highly interdependent teams to work closely together and progress at the same pace. These recommendations favor the teams working synchronously and with consistent information.

4.4.2.1.3 "Shifting the burden" system archetype: best guess

Generally, it is expected that the preliminary phases of a product development project will have knowledge gaps, a high level of uncertainty, known unknowns and unknown unknowns. The knowledge gaps are reduced or closed as the product development process is followed and the project evolves. However, to achieve the desired time to market, the organization chose to progress on the basis of the best guess, i.e., the best of the available knowledge.

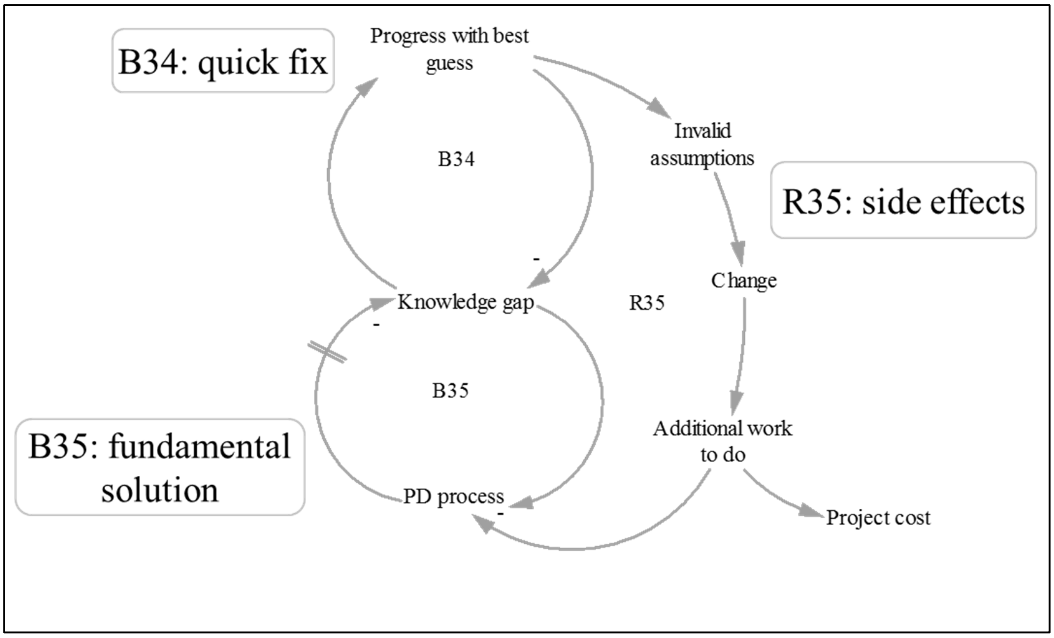
There is a risk to project performance associated with the decision to progress based on the best guess or to push the resolution of upcoming knowledge gaps. The risk is that when assumptions turn out to be invalid, the results are changes, additional work to do and increased project cost. Moreover, invalidating assumptions disrupts the product development process and new cycles may need to start based on new assumptions.

Modeling this event revealed that it matches the "shifting the burden" system archetype presented in Figure 4.20. The balancing loop (B34) connects the problem symptom variable and the quick-fix variable, which are the variables "knowledge gap" and "progress with best guess", respectively. To minimize the problem symptom of the knowledge gap, the quick fix of progressing with the best guess and figuring out the details later in the product development process was implemented. However, the balancing loop (B35) shows the fundamental solution of following the product development process because an increasing maturity of the product is expected when the project respects the maturity level in progressing to further phases.

The quick solution triggered side effects that made it even more difficult to implement the fundamental solution. The side effects are presented in the reinforcing loop (R35), which shows that progressing in the project with the best guessing may expose the project performance to the risk of invalidating assumptions, consequently leading to change, additional work to be done, increased project cost and disruption of the product development process.

Figure 4.20

Shifting the burden, best guess



(Melo, 2019)

One recommendation relies on ensuring that high-risk knowledge gaps are closed or reduced before allowing the product development to progress, as pushing past knowledge gaps represents high risk of disruptive downstream rework. A second recommendation relies on ensuring that the progress of highly interdependent teams is based on awareness of the information maturity level needed between them. Thus, the amount of effort can be managed according to the information maturity level, favoring collaboration and transparence between teams.

4.4.2.1.4 Combined fixes that fail system archetype: accidental adversaries adapted

The product development project performance depends on the performance of the suppliers and partners that are contracted for the project. Each organization has its own criteria in evaluating what being part of the project is worth. However, in the case study, the additional features that became necessary to deliver a competitive product led to EDR for the organization itself and for the suppliers involved in the project as the knock-on effects of the engineering changes.

The EDR led to additional work to be done, undermining the profit expected by the supplier. This in turn led to the supplier renegotiating the contract and engaging in the commercial dispute rather than proceeding with the project. This contributed to a continual erosion of the collaborative relationship between the suppliers and the organization. As the collaboration decreased, the technical solutions were not necessarily optimal, which triggered new EDR cycles.

Modeling this event revealed that it matches an adapted version of the "accidental adversaries" system archetypes, which resulted in a combination of two "fixes that fail" system archetypes, presented in Figure 4.21. The balancing loop (B46) connects the problem symptom variable and the quick-fix variable, which are the variables "optimal concept/design" and "change", respectively. Therefore, to minimize the problem symptom that does not achieve the optimal concept/design solution, the quick fix is to perform the necessary changes to the concept/design. The quick fix of the balancing loop (B46) results in an unintended consequence, which is the additional work to do and EDR, which in turn impacts the other balancing loop (B47).

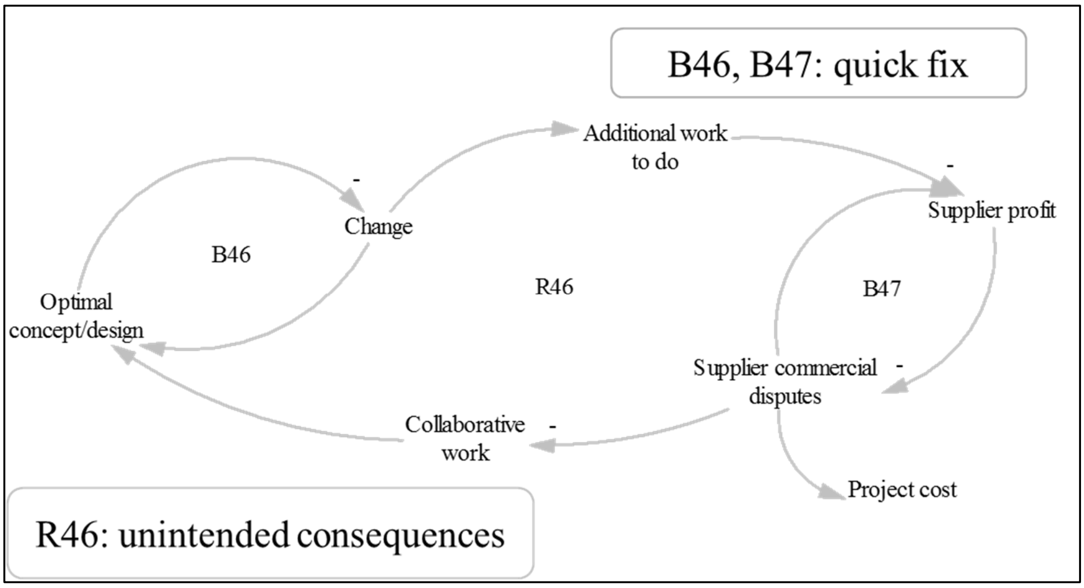
Balancing loop (B47) connects the problem symptom variable and the quick-fix variable, which are the variables “supplier’s profit” and “supplier commercial disputes”, respectively. To minimize the problem symptom, which is the reduced supplier profit due to the need to rework the design, the quick fix is to renegotiate the contract, initiating commercial disputes. The quick fix of the balancing loop (B47) results in an unintended consequence, which is the eroded relationship between the organization and the supplier, which reduces the collaborative work between them, which in turn impacts the other balancing loop (B46), reducing the proposal of the optimal concept/design. The combination of the unintended consequences for the balancing loops (B46 and B47) is the reinforcing loop (R46).

In summary, the initial relationship between the organization and the suppliers is expected to be a win-win relationship. However, as the project advances, each party is concerned with achieving its own success, and the results of their actions to do so may negatively impact the success of the other party, eroding the relationship between them throughout the product development project.

The recommendation relates to the high-leverage interventions that contribute to a sustainable win-win relationship between the organization and its suppliers throughout the product development project. The organization must provide suppliers with reliable product requirements, in such a way that the suppliers can better manage their efforts. The suppliers should be flexible in incorporating changes, as it is a product in development. Moreover, routine communication, collocated work sites, and collaborative attitudes between the involved parties are expected to contribute to a sustainable win-win relationship.

Figure 4.21

Combined fixes that fail: accidental adversaries adapted



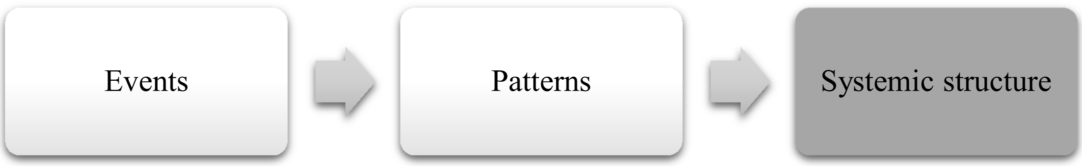
(Melo, 2019)

4.4.3 Systemic structure

The final conceptual framework is the third and last step of the postinterview phase, as shown in Figure 4.22.

Figure 4.22

Postinterview phase, systemic structure step



(Melo, 2019)

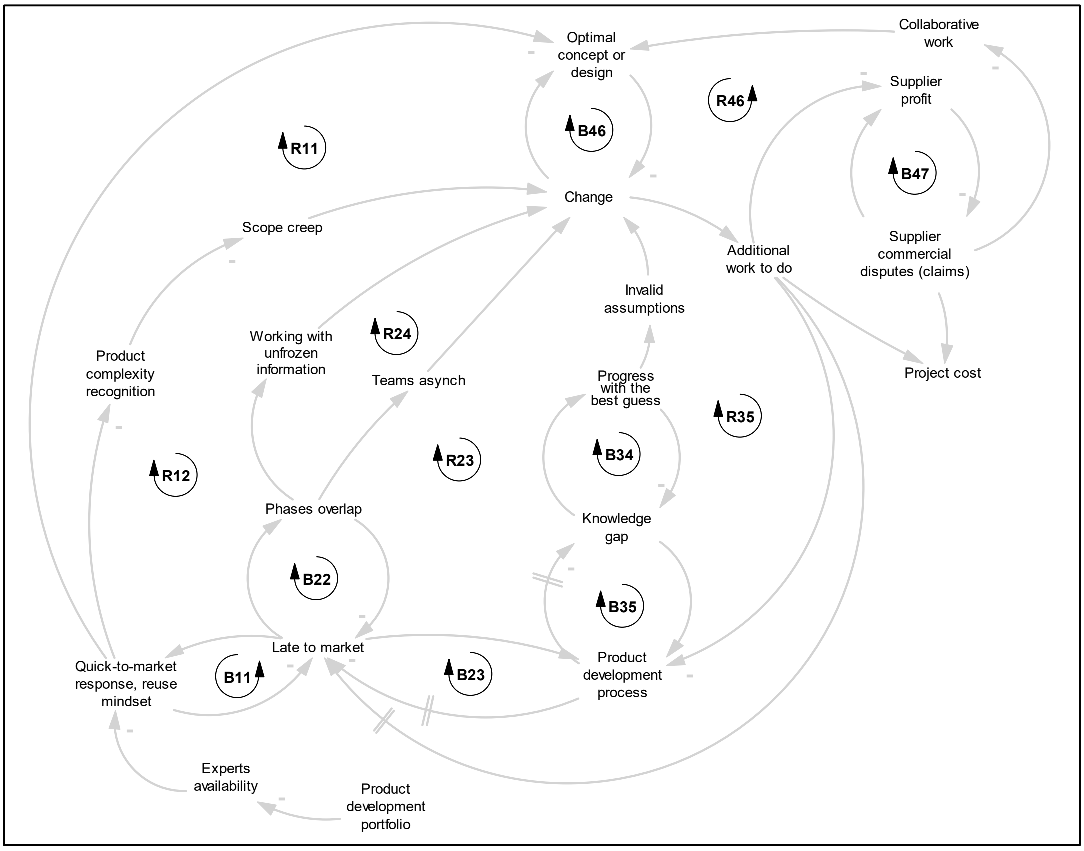
The combination of the four models identified in the previous section gives rise to the causal loop model, which represents the dynamics of rework in a complex product development project. The causal loop model comprises the variables and feedback relationships of the dynamics of rework that allow the final revision of the conceptual framework, which is the ultimate goal of this research. Additionally, recommendations to influence the dynamics of rework and improve project performance are proposed.

4.4.3.1 Causal loop model: dynamics of rework

The combination of the balancing and reinforcing loops between the variables identified during the data analysis of this study from Figure 4.18 to Figure 4.21 resulted in the overall causal loop model presented in Figure 4.23.

Figure 4.23

Causal loop model: dynamics of rework



(Melo, 2019)

The Figure 4.23 presents the variables identified during the data analysis concerning the dynamics of rework in a complex product development project. Additionally, the balancing and reinforcing loops represent the relationship between those variables as analyzed and described in §4.4.2.1. Understanding which the variables and their dynamics is the ultimate goal of this research and allowed the revision of the conceptual framework of this study.

4.4.3.2 Variables of the final conceptual framework

Objective 1 of this study was to identify the variables that comprise the dynamics of rework in complex product development projects. As shown in Table 2.7, there are five elements of interest of the conceptual framework: the first is the triggers of the dynamics of rework (x), the second is the static factors associated with the product development project (P), the third is the dynamic factor associated with the product development project (z), the fourth is the controlling factor associated with the product development performance (Z) and the fifth is the impact of the dynamics of rework on the project performance (y). Table 4.4 presents the correspondence between the elements of the conceptual framework and the variables proposed in the causal loop.

Table 4.4

Final conceptual framework variables and the causal loop variables

Conceptual framework elements		**Causal loop variables**
x	Triggers of the dynamics of EDR	Additional work to do, change, scope creep
P	Product development project static factors	PD process, teams' asynchronous work execution, collaborative work
z	Product development project dynamic factors	PD portfolio, PD expert availability, knowledge gap, product complexity recognition, invalid assumptions
Z	Product development project performance controlling factors	Quick-to-market response, reuse mindset, progress with best guess, phase overlap, work with unfrozen information
y	Product development project performance	Optimal concept/design, late to market, project cost, supplier profit, supplier commercial disputes (claims)

(Melo, 2019)

4.4.3.3 Feedback relationships between the variables of the final conceptual framework

Objective 2 of this study was to analyze the relationship between the variables of the conceptual framework. According to Table 2.8, there are five feedback relationships of interest: the relationships between triggers of the dynamics of rework (x) and project static factors (P); triggers of the dynamics of rework (x) and project performance controlling factors (Z); project dynamic factors (z) and project static factors (P); project dynamic factors (z) and project performance controlling factors (Z); and project performance (P) and project performance (y).

Table 4.5 presents the highlights of the feedback relationships identified in the causal loop model after the detailed and holistic analysis was undertaken previously in §4.4.2.1.

Table 4.5

Highlights of final conceptual framework variables and the causal loop variables

Relationship between conceptual framework variables	**Causal loop highlights**
Triggers of the dynamics of rework (x) and project processes (P)	EDR disrupts the product development process
Triggers of the dynamics of rework (x) and project performance controlling factors (Z)	Managerial decisions trigger EDR
Project dynamic factors (z) and project processes (P)	The project dynamics disrupt the product development process
Project dynamic factors (z) and project performance controlling factors (Z)	The managerial decisions contribute to increased project dynamics challenges
Project processes (P) and project performance (y)	Not following the PD processes reduces the project performance

(Melo, 2019)

4.4.3.4 Recommendations to influence the dynamics of rework and improve project performance

The causal loop model, Figure 4.23, encompasses the dynamics of rework in a complex product development project. From this holistic perspective, resulting from data collected and analyzed throughout this research, some recommendations are proposed as high-leverage actions to influence the dynamics of rework and improve project performance.

In general, the data analyzed in this research, comprising the three game-changing product development projects, the product development literature review and the complex product development project research case study, show that organizations that undertake complex product development projects are pursuing two main elements: reduced project duration and the satisfaction of the product performance requirements, including an evolving set of product requirements.

However, the aforementioned elements compete because they are parts of the complex and dynamic environment of the complex product development project. In the end, a project may deliver an outstanding product but at a high cost and later than predicted. Moreover, EDR was revealed to be a substantial contributor to the poor time and cost performance of product development projects, as discussed in this study. The main problem is the inability to accurately predict and avoid rework throughout product development projects because rework is embedded in the product development process.

Thus, the recommendations to influence the dynamics of rework and improve project performance are presented as follows.

Perform a robust product requirement management process and manage to have product development experts available, especially in the initial phases of the complex product development project, to ensure timely identification, validation and verification of the product requirements. This approach is expected to uncover unknowns and lead to a better understanding of the product complexity and better scope, budget and schedule for the project.

Reuse of previous product development information is recommended; however, two points must be observed. First, information reuse must be challenged and assessed in the new product development project context so that only added-value information is retained. Second, information reuse does not mean that the time needed to perform the associated activity will be reduced; however, the risk associated with the activity is mitigated.

The overlap of project phases should be managed carefully, and high overlapping of project phases is not recommended. However, the involvement of downstream teams in up-front phases is recommended for two main reasons. First, downstream teams, such as manufacturing and test teams, can provide insights to the product development team. Second, the downstream teams can be provided with valuable up-front information that they can use to plan their activities, contributing to streamline the project progress.

Interdependent product development teams should have clear visibility of the development activities sequence; they should work closely together and progress at the same pace within the product development project phase. In other words, they should work synchronously, in contrast to the usual practice of teams working in silos and trying to achieve purposeless schedule dates, resulting in asynchronous work execution, the sharing of outdated information and the consequent future need to rework.

Although knowledge gaps are expected in complex product development projects, those that represent high risk for the project should be closely managed. In addition, to ensure that the proper amount of effort is made by interdependent and downstream teams that are receiving information that is not frozen, it is recommended to clearly distinguish the condition of technical data, as preliminary versus validated, between teams, ensuring transparency and collaboration.

A sustainable win-win relation between the organization and its suppliers throughout the product development project is recommended. Thus, routine communication, collocated work, and a collaborative rather than opportunist attitude are important elements that contribute to the win-win relationship. Moreover, if an organization performs a robust product requirement management process up-front, the consequently improved scope, budget and schedule will contribute to better negotiations with suppliers before signing contracts and in the long term may reduce supplier claims.

4.5 RESULTS SUMMARY

The main objective of this research was to investigate the dynamics of EDR that negatively impacts the performance of complex product development projects. The main objective was split into two others: identify the variables of the dynamics of rework and the feedback relationships among the variables. The research results presented in this chapter are summarized as follows.

The research results presented in this chapter were obtained following the established strategy for data collection and data analysis presented in chapter 3, and Table 4.6 presents the correspondence between them.

Table 4.6

Summary of the strategy of data collection, data analysis and research results

	Chapter 3	Chapter 4
	Methodology	**Results**
Data collection – Preinterview phase	§3.5	§4.2
Participant observation and documentation analysis	§3.5.1	§4.2.1
Rich picture	§3.5.2	§4.2.2
First revision of the conceptual framework	§3.5.3	§4.2.3
Data collection – Interview phase	§3.6	§4.3
Semistructured interview preparation	§3.6.1	§4.3.1
Conducting and documenting the semistructured interviews	§3.6.2	§4.3.2
Data analysis – Postinterview phase	§3.7	§4.4
Events	§3.7.1	§4.4.1
Patterns	§3.7.2	§4.4.2
Systemic structure	§3.7.3	§4.4.3

(Melo, 2019)

A summary of the data collected in the research is presented in the Table 4.7.

Table 4.7

Data collected, including the applied technique, sample size and data source

Preliminary phase		**Preinterview phase**		**Interview phase**
Early findings		**Data collection**		
Qualitative technique				
Semistructured interview	Systematic literature review	Participant observation	Document analysis	Semistructured interview
Sample size				
7	93	12	~100	42
Data source				
Practitioners with experience in aviation product development projects	Web of Science database, Scopus database and Google Scholar search engine	Ad hoc meeting with organization professionals in finance, product development, and project management, among others	Assessment reports of product development projects, organizational procedures, project cost, schedule and technical change requests	Organization SMEs, managers, directors and section chiefs. Average experience in the project of six years

(Melo, 2019)

A summary of the system archetypes identified in the analysis of the case study is presented in Table 4.8.

Table 4.8

Summary of the system archetypes identified in the case study

Section	System archetypes	Model name	Brief description of the case study context
§4.4.2.1.1	Fixes that fail	Reuse mindset	The constrained project context led the organization to propose a quick-to-market solution based on a previous product version. However, the organization reuse mindset associated with the need for a competitive product led to an evolving understanding of the real project scope that triggered rework activities and undermined the capability of the organization to deliver the product under the forecast schedule and cost constraints.
§4.4.2.1.2	Shifting the burden	Phase overlap	The need to deliver a quick-to-market solution associated with the reuse mindset led the organization to overlap product development phases. Thus, the teams worked asynchronously and/or with unfrozen information, triggering rework activities that disrupted the product development process and undermined the capability of the organization to deliver the product under the forecast schedule and cost constraints.
§4.4.2.1.3	Shifting the burden	Best guess	The knowledge gap is higher in the project preliminary phases and decreases as the project evolves. However, due to the time-to-market pressure, the decision was made to progress with best guesses. Rework activities were triggered when assumptions turned out to be invalid, which disrupted the product development process and undermined the capability of the organization to deliver the product under the forecast schedule and cost constraints.
§4.4.2.1.4	Combined fixes that fail	Accidental adversaries adapted	The relation between suppliers and the organization was eroded by the additional features needed to assure a competitive product. This triggered rework activities and reduced the suppliers' profit. Thus, the project progress depended on resolving commercial disputes. In addition, the reduced collaboration between the parties led to technical solutions that were not necessarily optimal, which triggered rework activities.

(Melo, 2019)

CHAPTER 5 - DISCUSSION

The objective of this chapter is to discuss the results of this research. The results are compared to the managerial problem stated in the beginning of the study as well as the previous studies available in the literature. Then, the theoretical and managerial contributions of the study are presented, and potential future studies are envisaged. The chapter concludes with the identified strengths and weakness of this research.

5.1 RESEARCH RESULTS VERSUS MANAGERIAL PROBLEM AND LITERATURE REVIEW

In this section, the research results are compared to the managerial problem investigated in this study, which is the presence of EDR in product development projects and its influence on project performance. Additionally, the research results are compared to previous studies within the literature review perimeter of the topics: product development, project management and change.

5.1.1 Research results versus managerial problem

The following sections discuss the research results in relation to the presence of EDR in product development projects and its influence on the project performance.

5.1.1.1 Research results versus EDR

The academic and practical relevance of studying the EDR phenomenon was validated in this research. The literature considers rework a necessary evil of product development projects (Kennedy et al., 2014), meaning that it is necessary to perform corrections or adjustments to the product being developed; however, it is also disruptive to the project due to the rework knock-on effects.

Jarratt et al. (2010) cited other studies that consider engineering change a major source of problems in product development projects. Even though rework can consume 30 % to 50 % of an organization’s engineering capacity (Fricke et al., 2000; Hamraz & Clarkson, 2015; Loch & Terwiesch, 1999; A. Maier & Langer, 2011), it is accepted as normal in product development projects.

This duality of EDR being considered both good and bad, necessary and harmful to the product development project performance was also observed in the case study. Nevertheless, rework is a source of resource waste and should be eliminated so that an improved project performance can be delivered. This reinforces the importance of studying rework as a complex managerial problem.

The initial research results were obtained when the researcher contacted practitioners in the study preliminary phase and found that practitioners had two main strategies for dealing with rework. One was using product development quality gates to avoid pushing problems to later stages of the project, and the other was accepting the need to execute rework as something that happens after the fact, a reactive approach. Both strategies were identified in the product development project case study.

Studies on the dynamics of rework in the construction literature have found that the project budget, schedule and scope, additional and changed requirements, design changes, professional experience and complexity are the main causes of rework (Forcada et al., 2017; Forcada et al., 2014; Love et al., 2011). These factors were considered to be the triggers of the dynamics of rework variables in the preliminary conceptual framework of the study (Table 2.6).

The research results revealed that the dynamic of rework in the product development project was triggered mainly by variables similar to those identified in the construction literature, including tight schedule, scope creep, additional product requirements, experts’ availability, and lack of recognition of the product complexity. Additional variables include fast-tracking and design teams' asynchronous work, which are aligned with the vicious cycle of parallelism presented by Williams et al. (1995).

5.1.1.2 Research results versus product development project performance

Performance can be framed as effective and efficient (Drucker, 2011). The metrics to measure effectiveness and efficiency started purely as financial indicators and progressively incorporated other dimensions, such as project success and project management metrics (Kerzner, 2011, p. 77). Performance is summarized in four categories, presented previously in Table 1.1. Additionally, surveys prepared by PMI have communicated the actual state of project performance on the basis of the achievement of the initial objectives, budget, and schedule and how much the project scope changed (PMI, 2018).

Moreover, a literature review showed that studies on product development seek alternatives to reduce the product development cycle, consequently reducing the project cost. Additionally, as product development projects are business processes, reducing the development cycle may allow organizations to deliver products to market more quickly, increase their market share and stay ahead of the competition. That is why the preliminary conceptual framework shown in Table 2.6 considered project cost and development cycle duration to be the product development project performance variables that are particularly negatively affected by the dynamics of rework.

However, the research results demonstrated that in addition to the project cost and development cycle duration variables, the "optimal concept and design" of the product has a major role as a product development project performance variable. Because rework is a means to correct and adjust the product being developed, rework cycles are expected until the product design solution satisfies the product performance requirements, meaning "optimal concept and design".

The research results revealed that the product performance requirements evolve throughout the project life cycle, as they depend on competitors' products and market needs to ensure that the product being developed remains competitive. This result is supported by Fricke et al. (2000). Moreover, as the product complexity was revealed and because the schedule was tight, design contingencies were added to cope with the knowledge gaps, leading to nonoptimal design solutions, which in turn needed to be reworked until the product solution satisfied the product performance requirements.

Furthermore, the preliminary phases of the case study occurred in a highly competitive market context, imposing an aggressive project schedule, constrained budget and unavailable product development experts. This combination of factors contributed to the inadequate scope of the project. As revealed in the case study, the product performance was prioritized over the project schedule and budget, and the final product was outstanding; however, this prioritization contributed to the product development project cost overrun and delay.

5.1.2 Research results versus literature review

Hereafter, meaningful points observed in the literature review are compared with the research results. The literature review on rework was delimited by three main topics: product development, project management, and change.

5.1.2.1 Research results versus product development literature

The solutions proposed by the product development literature – to reduce the product development cycle duration and cost, which in turn is expected to reduce rework and improve project performance – rely mainly on alternative ways to define the optimal activities sequencing of the product development process. This includes planning the overlapping of sequential activities, evaluating the probabilities and impacts associated with the risk of rework that may undermine the benefits of overlapping sequential activities and planning communication between teams (Akkermans & van Oorschot, 2016; Browning & Eppinger, 2002; Krishnan et al., 1997; Lin, Qian, Cui, & Miao, 2010; Yassine, 2004).

In the preliminary conceptual framework Table 2.6, the product development process architecture, the integration of development teams in terms of communication and planned concurrency between product development activities were the variables that emerged from the literature concerning product development project static factors.

In the research results, the organization also needed to reduce the product development cycle duration and was constrained in terms of the project cost. An alternative was to develop a product based on a previous product version, which gave the organization strong confidence that the previous product information could be simply reused.

Considering the need to reduce the development cycle and the strong reuse mindset, these factors contributed to the managerial decision to highly overlap the product development phases to reduce the development cycle duration. However, as the project progressed, the product complexity was revealed and additional product requirements that were necessary to assure the product competitiveness further increased the product complexity.

In this context, mainly due to the product development phases overlapping, the teams were working with unfrozen information and information at different maturity levels, which consequently made them work asynchronously, resulting in disruptive rework cycles in the project.

Another aspect is collaborative work, referring to communication between teams. It was noted that in phases before the need of rework, there was more engagement in collaborative work and integration between teams. However, as rework started, and the teams had more activities to perform, the teams' engagement in collaborative work and integration decreased. This decrease represented another source of rework because as teams collaborate and integrate less, they are more likely to discover errors in downstream phases that lead to new rework cycles and contribute to project disruptions.

5.1.2.2 Research results versus project management literature

Management scholars and consulting professionals have reviewed complex projects through postmortem studies to understand the causes of complex projects being plagued by time and cost overruns (K. G. Cooper, 1980; Howick, Ackermann, Walls, Quigley, & Houghton, 2017; Williams, 2004). According to Williams (2005) the main causes are project complexity, uncertainty and time constraints, and Wysocki (2011) added *change* as a fourth cause.

Because of the aforementioned features of complex projects, reactive managerial decisions to control project performance result in counterintuitive effects, meaning that instead of controlling the project performance, as intended, the managerial decisions make the project situation worse.

In the preliminary conceptual framework shown in Table 2.6, fast-tracking sequential activities was the only variable identified in the literature review in terms of the product development project performance controlling factors because the literature revealed it as a common practice to rescue the project schedule to achieve the intended time-to-market. However, due to the features of complex projects, this action leads to results that are the opposite of the desired results, meaning that instead of reducing the project duration, it contributes to project disruptions that increase the project duration and cost.

The research results corroborate the findings of the literature review. The managerial decisions that resulted in counterintuitive effects included the fast-tracking of sequential activities, such as the decision to highly overlap the product development phases. This decision was reinforced by the initial project context of competition, an aggressive time-to-market target and the strong mindset of reusing the previous product information.

In this context, the managerial decisions were schedule-driven, which favored the underestimation of the project scope and the lack of recognition of the product complexity. The time constraint and the strong reuse mindset favored the decision for the project to progress on the basis of "best guess" and unfrozen information. Product requirements were added as the project progressed to ensure product competitiveness; however, this increased the project scope and product complexity. The long-term effects of those controlling decisions resulted in rework due to the additional requirements and invalidated assumptions.

According to the research results, from the beginning of the product development project until the middle of the project, the cost and schedule were major decision drivers. Consequently, management decisions were intended to achieve the aggressive target schedule and budget constraints. However, the project cost and schedule were continually challenged by the product performance, which means that as the product performance was not being achieved, rework was needed to correct and adjust the product. Thus, more time and cost were incurred to develop a product that would satisfy the product performance requirements. In this context, the long-term consequences of managerial cost- and schedule-driven decisions resulted in several rework cycles, which in turn contributed to project time and cost overruns.

5.1.2.3 Research results versus change literature

The dynamic, uncertain and iterative nature of product development projects is depicted by Karniel and Reich (2013, p. 19) and Ullman (2010) as the product development paradox, which refers to the fact that in the beginning of the project, less knowledge is available, yet it is when the most critical decisions are made. In addition, as the project advances, more knowledge is acquired; however, the product design freedom decreases because of previous decisions that have been made. Thus, changes to the project may be necessary due to the increased product knowledge and the invalidation of initial assumptions resulting in the need to rework previous activities (Karniel & Reich, 2011).

The literature revealed that in product development projects, product knowledge is acquired as the project progress, meaning that product knowledge is continuously evolving. Thus, rework can be initiated by upstream teams when they discover that their initial assumptions were invalid. In addition, downstream teams can provide feedback on relevant product knowledge that may require rework. These variables were considered the product development project dynamic factors in the preliminary conceptual framework Table 2.6.

The case study results are aligned with the literature. In the initial project context, competitiveness imposed an aggressive product time-to-market, and the fact that the organization was developing other products concurrently limited the project budget and experts availability. This combination reinforced the decision to reuse information from the previous product version, which gave the organization confidence that the product complexity was well understood.

However, as the project progressed, technical challenges were discovered, and additional product requirements were incorporated into the product solution. Thus, what was initially a reuse situation was transformed into the development of a much more complex product. The tight schedule and the overlapping of the project phases further exacerbated the situation and all contributed to the initiation of several rework cycles.

Although the organization had the necessary technical experts for developing its product development projects, the experts' availability was not properly managed, mainly because the organization was undertaking other concurrent product development projects that also needed their expertise. The contribution of the experts could have supported a better project scope and better recognition of the product complexity, which in turn could likely have reduced the later rework related, for instance, to scope creep and additional product requirements.

5.1.3 Research results versus managerial problem and literature summary

In this section, the research results were compared with the managerial problem, which is EDR in product development projects, its influence on project performance, and the existing results from the previous literature concerning product development, project management and change.

To highlight the dynamics of rework observed in the case study that impacted the project performance, the following paragraphs summarize the case study in three stages.

Stage 1: the preliminary phases of the case study occurred in a highly competitive market context, imposing an aggressive project schedule and constrained budget. Additionally, as the organization was undertaking other product development projects, the product development experts were unavailable. The organization decided to develop a product based on a previous product version, which gave it confidence that the previous product information could simply be reused. As a result, the project scoped was based on a reuse mindset, and the product complexity was underestimated.

Stage 2: the previous stage contributed to the managerial decision to highly overlap the product development phases and to allow the project to progress with knowledge gaps to reduce the project duration. However, as the project progressed, the product complexity and technical challenges were revealed. In addition, additional product requirements became necessary to assure the product competitiveness, which further increased the product complexity and initiated rework cycles. This combination of factors invalidated the project reuse scope, and the new project scope turned out to be much more complex. Nevertheless, the facts that unfolded in project stage 2 were exacerbated by the underestimations presented in stage 1.

Stage 3: the combination of overlapping project phases and the increased product complexity also initiated rework cycles that resulted from teams working with unfrozen information and with information at different maturity levels, which consequently made them work asynchronously. The rework resulted in more work to do and reduced the teams' engagement in collaborative work and integration, which in turn created another source of rework because as teams collaborate and integrate less, they are more likely to discover errors in downstream phases, leading to new rework cycles and contributing to project disruption.

Therefore, even though the final product was outstanding, the project performance in terms of time and cost did not meet expectations.

The summary of the analysis undertaken in this section is presented in Table 5.1.

Table 5.1

Research results versus managerial problem and literature review summary

Section **Research results versus**	**Research results summary**
Managerial problem	
§5.1.1.1 EDR	Rework was validated as a complex managerial problem, due mainly to the duality of its being both necessary and harmful to the product development project performance. Nevertheless, rework is a source of resource waste and should be eliminated or reduced.
§5.1.1.2 Product development project performance	Rework increases the project cost and development cycle duration. Additionally, rework is reinforced by the need to deliver a competitive product.
Literature review	
§5.1.2.1 Product development literature	High concurrency between project phases combined with an increased project scope due to additional product requirements resulted in rework, reinforced by asynchronous work-flow execution and reduced collaboration between teams.
§5.1.2.2 Project management literature	Time-to-market and reuse mindset, contributed to high overlap of the project phases and progress based on best guesses. However, when assumptions became invalid, they initiated rework cycles.
§5.1.2.3 Change literature	The project scope evolution from reuse to a complex product development on a tight schedule and the unavailability of the experts in the project preliminary phases increased the rework effects.

(Melo, 2019)

5.2 THEORETICAL AND MANAGERIAL CONTRIBUTIONS AND FUTURE RESEARCH

In this section, the theoretical contributions of this research, as well as the managerial contributions, are presented. Additionally, potential future research directions are identified.

5.2.1 Research theoretical contributions

As discussed in §2.3, the three research streams that sought solutions to improve product development project performance were highlighted: traditional project management practices, the DSM as a tool to better understand the interdependencies of project elements, and system dynamics modeling. This research intends to make a theoretical contribution to the aforementioned research streams, as presented the following sections.

5.2.1.1 Traditional project management research stream

The traditional project management research stream neglects interdependencies and the changing environment of the project (Lévárdy & Browning, 2009; Williams, 2005). In this stream, the practice of breaking the project structures down to reduce project complexity neglects the project interdependencies. Moreover, in this stream, there is a strong belief that focusing on a detailed project plan is enough to prevent changes during the project execution.

Although both practices, breaking down project structures and creating a detailed project plan, contribute to better project performance, they are not sufficient in the context of a complex product development project. The breakdown of parts of the project cannot cover the totality of work that should be undertaken in a complex product development project due to the intensity of its interdependencies and dynamics.

Due to the intrinsic emergent feature of a complex product development project, the decisions of tomorrow depend on the decisions of today, and they also depend on the internal and external factors of the project, such as expert availability and competitor products. Altogether, they provide a basis for considering a product development project as a continuously changing process, unlike the traditional project management stream perspective, where changes occur minimally.

The research results revealed a meaningful challenge in a complex product development project: initially, the product solution had to fit into a constrained time and cost plan; thus, the managerial decisions are mainly schedule and cost driven, impacting the product solution definition. As the project advanced, the product performance requirements were updated to keep the product competitive. The long-term effects of the initial schedule- and cost-driven decisions contributed to initiating rework cycles because the final product solution had to comply with the updated product performance requirements. Hence, in the case study, product performance requirements had priority over project time and cost targets.

Therefore, this study contributes to the traditional project management research stream in identifying this gap between traditional project management research and the results of this research. The gap concerns the fact that the techniques proposed by traditional project management are not sufficient to deal with the high level of uncertainty and integration in complex product development projects. Uncertainty refers to the unknown unknowns and the known unknowns (knowledge gaps), and integration refers to all the complex network of interconnectivity between the parts of the complex product being developed.

5.2.1.2 DSM research stream

The use of DSM to define an optimal product development process, as well as to identify alternatives to reduce the product development process cycle by means of the concurrent execution of sequential activities, has proven to contribute to better project performance (J. F. Maier et al., 2014). In addition, the DSM has been a powerful tool to identify process, product and team interdependencies, partially filling the gap identified in the traditional project management research stream.

On the other hand, the DSM research stream focuses mainly on technical aspects of the product development process, especially during the project planning phase, and neglects management decisions made during the process. These management decisions include the common practice of fast-tracking activities as a reactive control action to recover the project schedule. Whether the overlapping of sequential activities is a planned or a reactive control action, it involves the risk of rework becoming necessary, and, depending on the amount of rework needed, it may undermine the initial intention of reducing the development cycle duration in addition to increasing the project cost.

The results of this study demonstrated that the misperception of the project scope and the product complexity contributed to the managerial decision to highly overlap project phases in order to reduce the product development cycle. However, this overlap disrupted the product development process due to the need for additional product requirements and because of teams working asynchronously and with unfrozen information, among other reasons. The influence of the managerial decisions during the development process is not covered in the DSM research stream.

The contribution of the research results to the DSM research stream relies on the fact that DSM focuses mainly on the planning phase of the product development process architecture, meaning activities sequencing; however, it neglects the managerial decisions made during the project. The research results revealed that the decision to highly overlap the project phases was based on misperceptions of the project scope and product complexity, leading to several rework cycles that were reinforced by the product development project disruptions.

5.2.1.3 System dynamics research stream

Studies of system dynamics modeling on complex projects were initially motivated by litigation processes. Those studies were generally of long duration and involved interdisciplinary teams that included modelers, specialists and lawyers. The models aimed to replay previous project scenarios to be used as litigation process proof. On the other hand, the present study sought to provide a rigorous academic study concerning the dynamics of rework in a complex product development project using systems thinking and qualitative system dynamics modeling.

Systems thinking and system dynamics fill the gaps in the previous research streams because they take into account the project changing environment, project interdependencies, and short- and long-term effects of management decisions to control the project performance. This is possible because the dynamics of rework are being analyzed as a complex system.

A contribution of system dynamics modeling is to reveal how the management decisions to control the project performance result in counterintuitive effects; in other words, some decisions, instead of controlling the project performance, make it even worse. The reasons for this are the system complexity, interdependencies and nonlinearity between the variables.

Moreover, as far as the researcher is aware, no studies have been performed on the dynamics of rework in complex product development projects, and few such studies exist even in the construction literature. Thus, the contribution of this study to the system dynamics research stream was to investigate the dynamics of EDR in a complex product development project.

The results of the research allowed the proposal of a causal loop model of the dynamics of rework, which represents the achievement of the ultimate research goal. The causal loop model comprises the variables and the feedback relationships among the variables. System archetype structures were identified in the case study and were the basis for building the model. The main ideas of the model are highlighted in Table 5.2.

Table 5.2

Highlights of the causal loop model of the dynamics of rework

Model names	Causal loop model highlights
Reuse mindset	The reuse mindset of the organization does not allow it to properly identify the product complexity and project scope, which may lead to scope creep, EDR, increased project cost and delay.
Phase overlap	The aggressive time-to-market target may lead to project phase overlap, which in turn may lead to teams working asynchronously and with unfrozen information, resulting in EDR and thus disruptions in the product development process, increased project cost and delay.
Best guess	Despite recognizing the knowledge gaps, the management decision was made to progress by relying on the available knowledge; however, as the assumptions turned out to be invalid, EDR was initiated, increasing project cost and delay.
Accidental adversaries adapted	A win-win relation between the organization and suppliers established in the project initial phase turned into a sequence of commercial disputes due to additional product performance requirements, which initiated EDR in order to ensure product performance requirement compliance.

(Melo, 2019)

5.2.1.4 Research theoretical contributions summary

The summary of the theoretical contributions of this research is presented in Table 5.3.

5.2.2 Research managerial contributions

Three main managerial contributions of this study were identified: one concerning the study methodology, the second concerning the chain of causality of the object being studied and the third concerning the translation of the complex problem into organizational behavior. The managerial contributions are then discussed.

5.2.2.1 Research methodology

The research methodology is a managerial contribution; it included the use of soft systems thinking techniques, which allowed a holistic understanding of the dynamics of rework that did not neglect the context. The final rich picture (Figure 4.16) is one of the research results that represents the overall complexity of the case study being investigated.

Table 5.3

Research theoretical contributions summary

Research stream	Research theoretical contributions
Traditional project management	Even though traditional project management techniques are relevant to achieving improved project performance, they are not sufficient to manage complex projects. The research results revealed that dealing with project interdependencies and a changing environment is mandatory to succeed in the complex projects context, which is neglected by traditional project management. The research contributes by showing how difficulty is accomplishing product performance requirements impose several rework cycles, which negatively impacted project cost-time performance.
DSM	The DSM research focuses mainly on the planning phase of the product development process architecture; however, it neglects the managerial decisions that are made during the project. The research contributes by showing that the managerial decision to highly overlap the project phases, based on misperceptions of the project scope and product complexity, contributed to disrupting the product development process, initiating rework cycles that were reinforced by additional product requirements and by teams working asynchronously and with unfrozen information.
System dynamics	No studies were found concerning the dynamics of rework in complex product development projects, and few studies appeared even in the construction literature. The research contributes by providing a causal loop model of the dynamics of EDR in a complex product development project that is supported by the identification of recognized system archetypes.

(Melo, 2019)

The research methodology was tested in a real organizational environment under organizational constraints; for instance, the researcher was not allowed to record the semistructured interviews, she had a specific timeframe in which to conduct the interviews, and the techniques used for data collection had to be approved by the organization. Despite these organizational limitations, the research methodology (Figure 3.1, Table 3.3) was a successful means of collecting and analyzing the necessary data to investigate the complex organizational problem.

5.2.2.2 Chain of causality

The identification of the chain of causality of the main events related to the complex problem being investigated is a managerial contribution. The causal map (Figure 4.15) is the research result that presents the chain of causality and provides explanations about the management decisions that initiated EDR and negatively impacted the project performance in terms of time and cost. In complex problems, causes and effects are not necessarily close in space or time, which contributes to confusion in identifying problem symptoms and causes and this to noneffective project controlling actions because problem symptoms rather than causes may be treated.

Therefore, the chain of causality supported the identification of short- and long-term effects of the management decisions in the case study. The results are robust once they are triangulated based on the three main sources of data collection: participant observation, documentation analysis and semistructured interviews. Thus, avoiding similar decisions may mitigate the occurrence of EDR, which in turn may contribute to improving the project performance.

5.2.2.3 Events translated into organizational behaviors

The translation of the case study into systemic structures is a managerial contribution. It is presented in the research data analysis process (§3.7 and §4.4), in which the events of the case study are translated into systemic structures through the support of qualitative system dynamics modeling as well as recognized system archetypes, resulting in the causal loop model (Figure 4.23). It is a managerial contribution because the organization may reuse the translation process to investigate other organizational complex problem.

The identification of organizational behaviors is a managerial contribution. This represents a deeper understanding of the investigated complex problem because it is the organizational systemic structures that give rise to the patterns and events observed in the case study. The identification of the systemic structures means that recurrent organizational behaviors were made explicit. Acknowledging the systemic structure allows interventions with higher probabilities of solving or mitigating the presence of EDR in complex product development projects.

5.2.2.4 Research managerial contributions summary

The summary of the managerial contributions of this research is presented in Table 5.4.

Table 5.4

Research managerial contributions summary

Section	Research managerial contributions
§5.2.2.1 Research methodology	The research methodology using soft systems thinking techniques allowed a holistic understanding of the dynamics of rework. It was considered a successful means of collecting and analyzing the data in an organizational environment even given the organizational constraints.
§5.2.2.2 Chain of causalit	The causal map was based on three sources of evidence: participant observation, documentation analysis and semistructured interviews. It presents explanations of the short- and long-term effects of the management decisions that initiated EDR and negatively impacted the project performance.
§5.2.2.3 Events translated into organizational behaviors	The translation of the case study events into organizational behaviors allows a deeper understanding of the dynamics of rework. As the systemic structure gives rise to patterns and events, acknowledging the systemic structure allows efficient interventions that can help solve or mitigate the presence of EDR in complex product development projects.

(Melo, 2019)

5.2.3 Potential future research directions

Envisaged potential future research directions are described as follows.

This research identified relevant variables and relationships of the dynamics of rework in a case study. A further study could verify whether the same variables and relationships are meaningful in other complex product development projects and could propose critical success factors for reducing rework and improving project performance.

The access to the case study retrospective data allowed the research design to have a holistic perspective so that the big picture of an approximately ten years project could be assessed. A further study could consider the evaluation of the effectiveness of interventions in complex product development projects in reducing rework and improving project performance.

The main contribution of this research is the translation of a case study into organizational behaviors that may also be present in other complex product development projects. A further study could propose a tool to diagnose whether organizations that develop complex products have the same behavioral traits so that the rework challenges can be minimized.

As identified in the research results, the rework was also initiated by past managerial decisions, which in turn were based on misperceptions of the actual state of the project. Further research could define the dynamic leading indicators that could reduce this gap between the actual project state and the perceived state.

The case study demonstrated the richness of the data available to be analyzed. Further research could be based on reflections on how to incorporate the artificial intelligence domain to reduce uncertainty and make better decisions during the product development project in order to reduce rework and improve project performance.

5.3 STRENGTHS AND WEAKNESSES OF THE STUDY

In this section, the strengths and weaknesses of the study are presented.

5.3.1 Strengths

The strengths of the present study mainly concern the case study relevance, the time horizon covered in the research, the soft systems thinking methodology and the organizational behavior systemic structures identified.

5.3.1.1 Case study relevance

The case study was a one-of-a-kind complex product development project. The data access and the multiple sources of evidence contributed to rich research results. The participant observation process was undertaken for more than one year, at 20 hours per week. It allowed the possibility of analyzing the case study documents as well as the organizational process documents. In addition, the semistructured interviews enriched the data being assessed before the interview phase.

5.3.1.2 Longitudinal time horizon

EDR has been recognized as a managerial challenge that impacts product development project performance. Moreover, rework does not happen in isolation; on the contrary, it is a consequence of previous project decisions that initiate rework cycles. It occurs in a recurrent manner throughout the project. That is why it is important to have access to retrospective data to make it possible to understand the chain of causality of the main events concerning rework that happened during the project.

5.3.1.3 Soft systems thinking methodology

Another strength of this research is its reliance on the soft systems thinking and qualitative system dynamics modeling methodology to understand the complex problem being investigated. The advantage of this choice is its holistic perspective, as rework is a messy problem embedded in the product development project life cycle. In addition, its tools, such as the rich picture and the causal map, were suitable for use in the organizational environment.

5.3.1.4 Organizational behaviors

Finally, the ultimate research result, which is the causal loop model of the dynamics of rework, is considered a research strength as well. Through the case study analysis, a systemic structure was identified that extrapolated the case study specificity to a higher level, i.e., the identification of organizational behaviors that may be recognized in other complex product development projects within or outside the same organization.

5.3.2 Weaknesses

Despite all of the care taken during the phases of this research, the study may present some limitations. They concern the sampling, data collection and data analysis and are discussed in the following sections.

5.3.2.1 Sampling

Although the case study is a unique complex product development project to which the researcher had complete access, it concerns a single organization located in the aviation sector in Canada. Thus, full generalization is not possible, although the case study is likely representative as other aviation OEMs may face similar issues, including EDR, time-to-market needs, competitiveness and changing environment.

5.3.2.2 Data collection

The study was undertaken in the organizational context, and the researcher had no control over the events. Not all of the researcher's requests were accepted by the organization; for example, recording the semistructured interviews was not authorized, the initial time allocation for the interviews was a maximum of one hour per participant, and the number of questions in the interview guide was limited to 10.

As mentioned previously, this case study had a duration of approximately ten years, and approximately two thousand professionals were involved in the project. The researcher did not interview any executive at vice-president hierarchy level, project suppliers or procurement department professionals, which would be desirable. However, the researcher achieved information saturation after 12 ad hoc meetings and 42 semistructured interviews.

5.3.2.3 Data analysis

Recording the interviews was not allowed. The researcher's native language is Brazilian Portuguese and that of the environment is mainly Canadian English or French. Thus, some limitations are expected in capturing the information provided during the semistructured interviews.

CONCLUSION

The presence of EDR in product development projects was the complex managerial problem studied in this research. It was validated by practitioners as a relevant and real challenge for their organizations.

EDR is an intrinsic technical risk associated with complex product development projects because it is embedded in the engineering design process. Moreover, it is expected at any time throughout the product development process but cannot be fully anticipated, it is necessary to adjust the product but is simultaneously disruptive to the project, and it is triggered by a network of causes that influence each other. Some call it the necessary evil of product development projects (Godlewski et al., 2012; Kennedy et al., 2014).

In an extensive literature review and as far as the researcher is aware, no studies were found concerning the evaluation of the dynamics of rework in complex product development projects. Although the literature review revealed that the rework body of knowledge largely appears in the construction literature, recent studies have recognized the lack of systematic knowledge concerning the dynamics of rework, which makes it difficult to propose generalizations and predictability to address the rework problem (Forcada et al., 2017; Yap et al., 2019).

To better understand EDR phenomenon, this study objectively **evaluated the dynamics of engineering design rework that negatively impacts the performance of complex product development projects**.

The research objective was achieved through a case study analysis of a multibillion-dollar highly complex aircraft development project of 10 years' duration, involving hundreds of suppliers and thousands of professionals.

Due to the complexity of the dynamics of rework, the soft systems thinking methodology was chosen as the basis of the research data collection and analysis strategy. The soft systems thinking methodology is a holistic approach and has been used as an alternative to traditional project management to handle the complexity and the changing environment reality of projects (Jackson, 2003). It supports the identification of structures and patterns that underlie complex problems (Senge, 1994) so that high-leverage actions can be applied to the system structures to produce the desired results (Arnold & Wade, 2015; Sterman, 2000).

The preliminary phase and data collection phase of this research included 49 semistructured interviews, a systematic literature review covering 93 scientific documents, 12 ad hoc meetings within the professionals involved in the case study and analysis of approximately 100 documents of the organization case study (Table 4.7).

The data analysis followed the iceberg model described in (Stroh, 2015, p. 37). The iceberg model allowed the understanding of the dynamics of rework to move through three layers of the iceberg: *events*, *patterns* and *systemic structure*. As shown in Table 3.3, the layers correspond to the case study history, the identification of behavior patterns and the dynamics of rework, respectively.

The *events* layer includes the holistic understanding of the managerial problem context, the main facts, the stakeholders, the decisions made and the available options. The causal map and the rich picture were techniques of soft systems thinking used to depict the case study events that were gathered during the data collection.

The *patterns* layer represents the perspective of a deeper understanding of the dynamics of rework. System archetypes are used because they are generic patterns of behaviors previously identified in the literature (Rehak et al., 2006). Thus, four models were built based on two system archetype structures identified in the collected data. The models are summarized as follows.

Reuse mindset model: the constrained project context led the organization to propose a quick-to-market solution based on a previous product version. However, the reuse mindset associated with the need for a competitive product led to an evolving understanding of the real project scope, which triggered rework activities and undermined the capability of the organization to deliver the product under the intended schedule and budget constraints.

Phase overlap model: the need to deliver a quick-to-market solution associated with the reuse mindset led the organization to overlap product development phases. Thus, the teams worked asynchronously and with unfrozen information, triggering rework activities, disrupting the product development process and undermining the capability of the organization to deliver the product under the intended schedule and budget constraints.

Best guess model: the knowledge gap is greater in the project preliminary phases and decreases as the project evolves. However, due to the time-to-market pressure, the decision was made to progress with best guesses. Rework activities were triggered when assumptions turned out to be invalid, which disrupted the product development process and undermined the capability of the organization to deliver the product under the intended schedule and budget constraints.

Accidental adversaries adapted model: the win-win relationship between the suppliers and the organization became eroded by the additional product requirements needed to assure a competitive product. This triggered rework activities and reduced the suppliers' profit. Thus, the project progress depended on resolving commercial disputes. In addition, the reduced collaboration between the parties led to technical solutions that were not necessarily optimal, which triggered rework activities.

The *systemic structure* layer represents the mechanism that gives rise to the previous layers' results and represents the achievement of the ultimate goal of this research. The causal loop model, Figure 4.23, represents the systemic structure of the dynamics of rework in a complex product development project and summarizes the main variables and feedback relationships between the variables identified in the case study.

The main variables revealed in the dynamics of rework are the development team asynchronous work execution, collaborative work, product development expert's timely availability, product complexity recognition, invalid assumptions, quick-to-market response, reuse mindset, progress with best guess, phase overlap, working with unfrozen information, supplier commercial disputes, and optimal product concept and design.

The final conceptual framework of this study encompasses the dynamics of rework in a complex product development project. From this holistic perspective, resulting from the data collected and analyzed throughout this research, some recommendations are proposed as high-leverage actions to influence the dynamics of rework and improve project performance. They are described as follows.

Perform a robust product requirement management process. Manage to have product development experts available in the initial phases of the project. Challenge the previous product development information to ensure that only added-value information is reused. Highly overlapping project phases should be avoided. The upstream involvement of downstream teams provides valuable insights to the product development teams. Interdependent product development teams should have clear visibility of the development activities sequence and of the maturity level of the information they exchange. In addition, interdependent product development teams should progress at the same pace within the product development project phase.

Three theoretical contributions of this research are highlighted.

The first relates to the traditional project management research stream, which neglects the project interdependencies and changing environment. The research contributes by showing that addressing those elements is mandatory to manage complex product development projects successfully.

The second relates to the DSM research stream, which, even though it aims for optimal product development process architectures, neglects managerial decisions throughout the project life cycle. The research contributes showing that managerial decisions based on misperceptions of the project scope and product complexity contributed to the disruption of the product development process.

The third contribution relates to the system dynamics research stream, where no studies were found concerning the evaluation of the dynamics of rework in complex product development projects. The research contributes by providing a causal loop model of the dynamics of rework supported by the identification of recognized system archetypes.

Three managerial contributions of this research are highlighted.

The first relates to the research methodology using soft systems thinking techniques, which allowed a holistic understanding of the dynamics of rework, resulting in a successful means of collecting and analyzing the data in an organizational environment.

The second relates to the chain of causality using the causal map tool based on three sources of evidence: participant observation, documentation analysis and semistructured interviews. It presents explanations for the short- and long-term effects of the management decisions that initiated rework and negatively impacted project performance.

The third relates to events translated into organizational behaviors, allowing a deeper understanding of the dynamics of rework. Systemic structures give rise to patterns and events; thus, acknowledging the systemic structures favors the identification of high-leverage interventions to solve or mitigate EDR in complex product development projects.

This study aimed to better understand the dynamics of rework in a complex product development project. The academic literature and organizations are converging in the direction of seeking alternatives to reduce the product development duration to achieve rapid time-to-market and reduce product development costs while simultaneously delivering a product that satisfies the evolving requirements to keep the product competitive. However, due to the structural complexity and the dynamics of those projects, short-term managerial decisions to control project performance, in terms of time and cost, result in nonoptimal product solutions in the long-term that initiate rework cycles, which in turn undermine the initial project time and cost targets. Thus, EDR contributes to those counterintuitive effects as it unfolds knock-on effects due to the product complexity and the interdependence of its parts and systems.

Therefore, acknowledging the dynamics of rework, i.e., its systemic structure, and applying high-leverage actions to influence the systemic structure are the first steps in the direction of improving project performance.

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ANNEX A

DISTRIBUTION OF PUBLICATIONS SOURCES BY AREA

Table A.1

Distribution of publications sources by area

Publications' source	[%]	
Construction	33	31
Architectural Engineering and Design Management	1,08	1
Automation in Construction	1,08	1
Civil Engineering and Environmental Systems	1,08	1
Construction Management and Economics	1,08	1
IEEE Transactions on Engineering Management	2,15	2
Information & Management	1,08	1
Interdisciplinary Description of Complex Systems	1,08	1
International Journal of Project Management	4,30	4
International Journal of Sustainable Construction Engineering and Technology	1,08	1
Journal of Construction Engineering and Management	7,53	7
Journal of Engineering Design and Technology	1,08	1
Journal of Infrastructure Systems	1,08	1
Journal of Management in Engineering	2,15	2
Journal of Performance of Constructed Facilities	1,08	1
Organization Technology and Management in Construction	1,08	1
Proceedings of the 6th Annual Meeting of the International Group for Lean Construction	1,08	1
Production Planning & Control	2,15	2
Structural Survey	1,08	1
System Dynamics Review	1,08	1
Product	40	37
Academy of Management. The Academy of Management Review	1,08	1
Advanced Engineering Informatics	1,08	1
Concurrent Engineering-Research and Applications	2,15	2
Design Science	1,08	1
European Journal of Operational Research	4,30	4
IEEE Transactions on Engineering Management	4,30	4
International Conference on Concurrent Engineering: Research and Applications	1,08	1
International Design Engineering Technical Conferences Computers and Information in Engineering Conference	2,15	2
Journal of Business Research	1,08	1
Journal of Mechanical Design	3,23	3
Management Research News	1,08	1
Management Science	2,15	2
Production and Operations Management	1,08	1
Research in Engineering Design	3,23	3
System Dynamics Review	1,08	1
Systems Engineering	2,15	2
Technovation Elsevier	1,08	1
Urbana	1,08	1

Publications' source	[%]	
Journal of Engineering Design	1,08	1
Organization Science	1,08	1
Quality and Reliability Engineering International	1,08	1
International Journal of Productivity and Performance Management	1,08	1
IIE Transactions	1,08	1
Software	10	9
10th International Symposium on Software Metrics (METRICS'04)	1,08	1
European Journal of Operational Research	1,08	1
IBM Systems Journal	1,08	1
International Journal of Software Engineering & Applications	1,08	1
Journal of Systems and Software	1,08	1
Management Science	1,08	1
MIS Quarterly executive	1,08	1
Software, IEEE	1,08	1
IEEE Transactions on Software Engineering	1,08	1
Project	17,20	16
Concurrent Engineering-Research and Applications	2,15	2
Engineering Management, IEEE Transactions	1,08	1
Interfaces	2,15	2
International Journal of Project Management	2,15	2
Management Science	2,15	2
Project Management Journal	2,15	2
Research in Engineering Design	1,08	1
System Dynamics Review	3,23	3
Unpublished manuscript, Cambridge, MA	1,08	1
Total	100,00	93

(Melo, 2019)

ANNEX B

INTERVIEW REPORT TEMPLATE

Interview Report Template

Date :	**Time** :	**Place** :
Interviewee : [Subject]		
Role in the project :	**Team** :	
Project working period(s) :		
Background :		
Additional information :		

Interview notes

ANNEX C

LETTER OF THE UQTR ETHICS COMMITTEE

UQTR
Université du Québec
à Trois-Rivières
Décanat de la recherche et de la création

Le 13 novembre 2018

Érika Souza de Melo
Étudiante
Département de management

Madame,

Pour faire suite à votre courriel du 12 novembre 2018 concernant le projet *Engineering design rework in product development projects: a Canadian OEM case study*, je vous confirme que certificat d'éthique n'est pas requis.

En effet, votre projet de recherche comporte des interactions avec des personnes qui ne sont pas elles-mêmes visées par la recherche, en vue d'obtenir de l'information. Par exemple, un chercheur peut recueillir, auprès d'employés autorisés à communiquer des renseignements ou des données dans le cours normal de leur travail, de l'information au sujet d'organisations, de politiques, de méthodes, de pratiques professionnelles ou de rapports statistiques. Ces personnes ne sont pas considérées comme des participants aux termes de l'Énoncé politique des trois conseils- EPTC2 sur l'éthique de la recherche avec des êtres humains, article 2.1, p.15).

Si vous avez besoin de renseignements supplémentaires, vous pouvez communiquer avec moi (819-376-5011, poste 2129, ou par courriel à cereh@uqtr.ca) pour en discuter.

Veuillez agréer, Madame, mes salutations distinguées.

LA SECRÉTAIRE DU COMITÉ D'ÉTHIQUE DE LA RECHERCHE

FANNY LONGPRÉ
Agente de recherche
Décanat de la recherche et de la création

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