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QUANTITATIVE RISK ASSESSMENT:

METHODOLOGY AND APPLICATION IN AN AUTOMAKER BODY-IN-WHITE PRODUCTION LINE PROJECT

AVALIAÇÃO QUANTITATIVA DE RISCOS: METODOLOGIA E APLICAÇÃO EM PROJETOS DE LINHAS DE BODY-IN-WHITE

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ABSTRACT

Purpose: this research aims to introduce a novel methodology, termed Quantitative Risk Assessment for body-in-white projects, to forecast the expected project completion time and total project cost. This methodology is demonstrated through application to a real project within an automotive manufacturer in Brazil.

Theoretical framework: the study employs established risk analysis methods (e.g., program evaluation and review technique, preliminary hazard analysis, Gaussian curve, Monte Carlo simulation) alongside project management tools for problem characterization (e.g., project requirements, assumptions, work breakdown structure).

Methodology/Approach: the methodology presented in this paper follows a sequence of methods that: (i) identify the hazards; (ii) evaluate the probability of risks associated with each project task; (iii) assess their consequences and impact on project costs; and, finally, (iv) quantify the risks to predict a probability spectrum for the project's total cost. This allows estimating an emergency reserve and categorizing the risk level to inform stakeholders.

Findings: The paper reveals that, among the 66 identified hazards, there is a 37% probability of the project duration exceeding 200 days, and the project has been categorized as high risk (i.e., more than a 20% probability that additional costs will exceed 20% of the estimated project budget).

Research, practical & social implications: this study enables organizations to forecast the potential impacts of risks on project schedules and costs through comprehensive risk assessments, providing valuable input for project risk management.

Originality/ Value: the study's value lies in the originality of its risk assessment methodology applied to automakers' body-in-white projects.

Keywords: Automaker; Body-in-White. Monte Carlo Simulation. Probabilistic modeling. Quantitative risk assessment.

RESUMO

Objetivo: O objetivo deste estudo é de apresentar uma nova metodologia chamada avaliação quantitativa de riscos para projetos em body-in-white, com intuito de prever o provável tempo necessário para a conclusão do projeto e custo total, através da aplicação real em uma montadora de veículos no Brasil.
Referencial Teórico: O artigo utiliza de métodos de análise de riscos (e.g., program evaluation and review technique, análise preliminar de riscos, curva gaussiana, simulação de Monte Carlo) and ferramentas de gestão de problemas para a caracterização do problema (e.g., premissas, requisitos de projetos, estrutura analítica de projetos).
Metodologia/Abordagem: A metodologia apresentada neste artigo segue uma sequência de métodos que, primeiramente, (i) identifica os riscos; em seguida, (ii) avalia a probabilidade dos riscos aplicados em cada tarefa do projeto; (iii) avalia suas consequências e impacto nos custos do projeto; e, por último, (iv) quantifica os riscos para prever um espectro da probabilidade do custo final do projeto, a fim de estimar uma reserva de emergência e categorizar o nível de risco para reportar aos stakeholders.
Resultados: Este estudo mostra que, dados os 66 perigos identificados, há uma probabilidade de 37% do projeto se estender por mais de 200 dias, e o projeto foi categorizado como de alto risco (ou seja, mais de 20% de probabilidade de o custo adicional ser superior a 20% do custo estimado do projeto).
Contribuições, implicações práticas e sociais: O estudo permite que organizações prevejam os prováveis impactos de riscos no cronograma e nos custos do projeto por meio de avaliações de risco e usem essas informações como entrada para o gerenciamento de riscos do projeto.
Originalidade/Valor: O valor do estudo se deve à originalidade de sua metodologia de aplicação de avaliação de riscos em projetos de carrocerias de automóveis.
Palavras-chave: Fabricante de automóveis. *body-in-white*. Simulação de Monte Carlo.Modelagem probabilística. Avaliação quantitativa de riscos.

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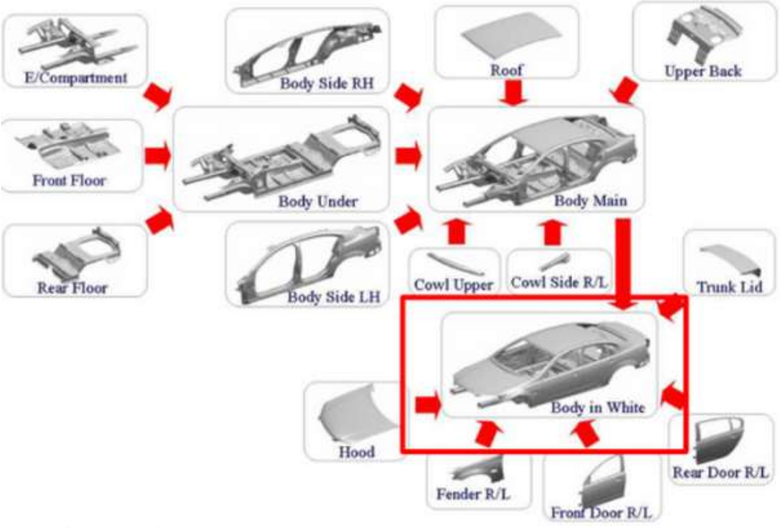
1. INTRODUCTION

New car launch projects in body-in-white (BiW) production lines (i.e., the stage in production where the car body is manufactured) (Figure 1) face numerous challenges. Key challenges include: (i) modifications to the production line during the project, which impact the production of current car models; (ii) changes in product design throughout the project; and (iii) the need for the project schedule to align with product milestone schedules. Consequently, these challenges can lead to potential project delays and extra costs (i.e., negative financial impacts). Several methodologies exist to support risk analysis in projects (Barbosa et al., 2019; Declerck, 2002; Duarte, 2011; Freeman, 1990; Hayes, 2019; PMI, 2018; Tag, 2017). However, none of these methodologies specifically address the impact of risks on individual project tasks and budgets, nor do they forecast their total influence on schedules and expenses within a probability spectrum. To fill this gap, this paper improves a quantitative risk assessment methodology to assess risks in a project's schedule and communicate to decision-makers.

Figure 1

Welded car body parts.



Source: Adapted from Azuko Technical Institute (2019).

Risk is defined by the hazard, its likelihood of occurrence, and the magnitude of the undesired consequence (Duarte, 2011). However, the unwanted consequences examined in this paper are specifically focused on financial impacts and potential delays in a BiW production line project.

Risk assessment is a crucial component of risk analysis, which also includes two complementary elements: (i) risk management and (ii) risk communication (Teaf, 2004). Risk assessment and communication are closely related, aiming to gather sufficient data to inform risk models, with results then communicated to decision-makers and stakeholders. In contrast, the primary focus of risk management is to propose measures to prevent risks or mitigate their impacts.

The automotive industry encompasses the design, manufacturing, and trade of vehicles within a specific region. In 2018, Brazil reported a 14.6% increase in vehicle production compared to the previous year, reaching a total of 2.5 million vehicles sold, according to data from the National Association of Motor Vehicle Manufacturers (ANFAVEA, 2018). Revenue generated from vehicle sales in Brazil in 2019 was approximately US$14 billion, supporting the employment of a total of 120,000 workers across automakers and their suppliers (ANFAVEA, 2019). In 2021, despite the global crisis, the volume of automobiles sold surpassed 2 million units (ANFAVEA, 2021).

The BiW production stage is typically one of the most complex phases in vehicle design due to the high level of technology and precision required (Pellegrinelli et al., 2017). Furthermore, BiW contributes, on average, to 27% of a vehicle's total weight and is a key stage in determining vehicle performance in terms of design, safety, and aerodynamics (Pradeep et al., 2017).

The objective of this paper is to propose a generalized methodology for quantitative risk assessment in BiW projects (QRABiW) that can serve as a practical guide for application in projects within this field. Additionally, it illustrates the methodology's practical application through a real-world project at a Brazilian automaker. As an added tool to support risk management, the methodology presented in this paper enables project managers to estimate a financial contingency aligned with the identified risks, thereby helping to prevent project setbacks. It is important to note, however, that this paper focuses solely on threat assessment and does not address opportunity assessment.

This research is structured as follows: the second section introduces the problem characterization. The third section identifies the hazards and evaluates the risks associated with the problem. The fourth section assesses the frequency of these risks. The fifth section evaluates their impacts on project cost and delay. Finally, the sixth section quantifies and categorizes the risks.

2. LITERATURE REVIEW

This research integrates knowledge from quantitative risk assessment, project management tools, and the BiW process to develop its methodology.

2.1 Risk assessment

Due to the complex interactions among humans, materials, ecosystems, and meteorological factors, Azevêdo et al. (2021) developed a flexible method for assessing ecological and microbial risks. Similarly, this complexity applies to meteo-oceanographic factors in shipping, prompting Azevêdo et al. (2021) to create a methodology for qualifying and classifying risks identified at Suape Port. Both studies follow a sequence of steps for quantitative ecological risk assessment (QERA), which includes problem characterization, hazard identification and consolidation of scenarios, risk evaluation of scenarios with a severity rating above "low", assessment of consequences with a frequency rating above "very low", and finally the risk categorization.

Ericson (2005) applies Preliminary Hazard Analysis (PHA) to assess 40 risks associated with missile launching, detailing each missile system component, its hazards, and likely consequences. In this project, PHA supports safety and design decision-making early in the development process, providing insights into where safety and design resources should be allocated throughout the program.

Hayes (2019) compiles the most effective methods used in risk assessment, such as Monte Carlo simulation, which employs random variables to predict probabilistic events; fault tree analysis, which identifies potential causes of unexpected events using a block diagram; and additional methods that enable quantitative risk assessment.

In automotive manufacturing, Failure Modes and Effects Analysis (FMEA) is essential for stabilizing production and enhancing competitiveness by identifying and prioritizing potential failures using Risk Priority Numbers (RPN). However, traditional FMEA has limitations, notably in assuming equal weight for severity, occurrence, and detectability, which can hinder accurate risk prioritization. To address these gaps, recent studies integrate Grey Relational Analysis (GRA) with FMEA, refining RPN by applying weighted importance to different factors. This GRA-FMEA approach has proven effective in automotive settings, enabling precise prioritization and mitigation of production failures. For instance, Baynal et al. (2018) showed that this method led to a 96% reduction in door seal cuts and resolved other assembly issues, illustrating its value in advancing risk management in complex automotive manufacturing processes.

The risk assessment methodology from Azevêdo et al. (2021), initially applied to ecological and microbial risks, can be effectively adapted for a BiW car launching project. By the PHA method, risks can be identified and qualified early in the process, ensuring thorough risk evaluation. Additionally, Monte Carlo simulation enhances this approach by forecasting the potential financial impacts of risks on the project budget, offering a probabilistic view that aids risk management. This combination provides a robust framework for comprehensive risk assessment in automotive projects.

2.2 Program evaluation and review technique

In projects, it is common to encounter more than a hundred tasks to be executed and managed. Barbosa et al. (2019) apply the Program Evaluation and Review Technique (PERT) to a 33-foot boat construction project to create a network diagram. This tool enables the project manager to estimate the duration of each task and path based on optimistic, likely, and pessimistic time estimates. Additionally, it helps identify the critical path (i.e., the sequence of tasks that defines the minimum time required to complete the project).

The PERT tool, as presented in Barbosa et al. (2019), offers a valuable approach for linking identified and qualified risks to individual tasks within the project schedule. By integrating PERT, it becomes possible to estimate the optimistic, pessimistic, and most likely timeframes for executing each task, based on the associated risks. This enables a more accurate prediction of how risks may influence the overall project timeline. Additionally, the method provides a quantitative basis for assessing schedule uncertainty, allowing for improved forecasting of potential delays and a more informed evaluation of the risks' impact on the project's total duration.

Recent studies have explored the integration of behavioral dynamics, particularly those encapsulated in Parkinson’s Law, into project management frameworks to improve activity scheduling and completion predictions. One notable contribution is a modeling framework developed by Gutierrez & Kouvelis (1991) which incorporates the behavioral tendencies of workers and subcontractors, as articulated in Parkinson’s Law, to predict the completion times of project activities. The study introduces an analytic model that represents completion time as a function of the deadline set by the project manager and the actual workload required. This model enables project managers to gain insights into how allocated time affects worker productivity, revealing that overly generous timelines may lead to inefficiencies, while overly tight deadlines could compromise quality or cause delays. Furthermore, Gutierrez & Kouvelis (1991) examine the impact of information release policies on subcontractor performance, analyzing which approaches might unintentionally extend project timelines. Their findings guide setting optimal deadlines for sequential and parallel tasks, offering project managers a structured approach to enhance task management and reduce project overruns.

The PERT methodology was preferred instead of CCPM (Critical Chain Project Management), (Leach, 2000) because it better addresses projects with high uncertainty in task durations. PERT uses probabilistic time estimates, providing a flexible, risk-sensitive approach to scheduling, ideal for scenarios where precise timing is difficult to predict. In contrast, CCPM, which focuses on optimizing resources and protecting the critical chain with time buffers, is better suited for projects with stable timelines and resource constraints. Thus, PERT's probabilistic framework makes it more suitable for a project schedule risk assessment.

2.3 Project management

A project is a temporary endeavor undertaken to create a unique product, service, or result. It has a defined start and end date, specific objectives, and constraints such as time, cost, and resources (PMI, 2018). Projects are typically designed to achieve strategic goals, solve problems, or deliver improvements. Unlike operational work, which is ongoing and repetitive, projects are characterized by their temporary nature and the uniqueness of their outcomes. Effective project management is crucial to ensure that the project is completed successfully within the specified parameters of scope, budget, and schedule.

Project scope refers to the detailed set of deliverables or tasks that must be accomplished to complete a project (PMI, 2018). It defines the boundaries of the project, outlining what is included and what is excluded. A well-defined project scope helps ensure that all stakeholders have a shared understanding of the project's objectives and deliverables.

PMI (2018) describes the Work Breakdown Structure (WBS) as a hierarchical tool used to break down a project into smaller, manageable parts, making it easier to plan and control. It starts with the overall project at the top and progressively divides it into phases, deliverables, and tasks. This structure helps in resource allocation, scheduling, cost estimation, and risk management.

Additionally, the WBS serves as a communication tool by clarifying the project scope for all stakeholders. Each component is assigned a unique identifier for tracking progress, and the WBS can adapt as the project evolves, providing a solid base for effective planning and execution.

In quantitative risk assessments for vehicle launch projects in BiW lines, the integration of the WBS and a well-defined project scope significantly improves risk management. By decomposing the project into specific tasks and deliverables, the WBS facilitates the identification of potential risk points associated with each project phase. This structured approach allows for the systematic association of risks with time, cost, and resource constraints, leading to more accurate estimations of their impacts on the schedule and budget. Additionally, the hierarchical nature of the WBS enhances resource allocation for risk mitigation and improves stakeholder communication. This fosters a shared understanding of risk implications and enables timely adjustments to the project plan, ultimately reducing uncertainty and enhancing the effectiveness of risk assessment in the vehicle launch process.

2.4 Automakers' body-in-white

To assemble the complete vehicle body, automakers may require hundreds of robots with varying reach and load capacities. This high level of complexity introduces risks throughout the design, construction, and implementation of these lines. The risk assessment study in this work is focused solely on its applicability to BiW line projects, i.e., production line configurations in automakers intended for the launch of a new vehicle (Patchong et al., 2003).

Patchong et al. (2003) demonstrate that Peugeot Citroën (PSA) aimed to revolutionize the automotive industry by using shared production platforms to manufacture a wide range of car models on the same BiW lines. As a result of such a strategy, production output increased by 4%, with a projected 90% increase in the coming years. However, PSA identified hazards related to the impact of the new models on the quality of existing car models.

Pellegrinelli et al. (2017) present a method for designing automotive BiW cells, focusing on technical analyses to minimize collision risks between robots and fixtures in a multi-robot spot-welding cell. The method includes cycle time analysis, fixture distribution, determination of the number of robots and tools needed for the operation, robot model selection based on required payload and range, and offline programming of robot trajectories.

The use of shared production platforms for various car models, as implemented by PSA (Patchong et al., 2003), demonstrates both the efficiencies and the risks of BiW lines, particularly regarding quality impacts on existing models. Similarly, Pellegrinelli et al. (2017) highlight methods to optimize BiW cell design by addressing robot reach and load capacities, which are essential for minimizing disruptions. These studies underscore the need for a targeted risk assessment methodology, as presented in this paper, to quantify and manage the risks affecting project costs and schedules in BiW line projects.

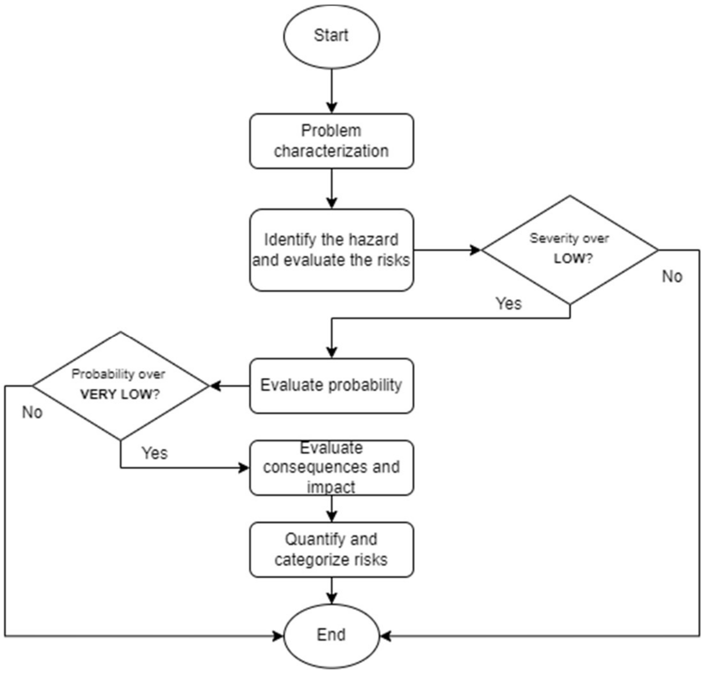
3. METHODOLOGY

In this section, we address a key objective of the paper by proposing a new, flexible quantitative risk analysis methodology, termed QRABiW. This methodology is specifically designed to assess the influence of each identified risk in the BiW project, evaluating its impact on both the schedule and budget within a probabilistic framework. QRABiW allows for a comprehensive risk assessment by incorporating probability distributions to capture uncertainty, thereby offering project managers a more nuanced understanding of how individual risks affect project performance and financial outcomes.

The steps for the risk assessment in this paper are structured as shown in Figure 2. Additionally, each equation and parameter used in this risk assessment is detailed in Table 1 for reference.

Figure 2

QRABiW flowchart



Source: Authors, 2024.

Table 1
Parameter's index

Parameters	Symbol	Description	Considerations/Equations
Likely time	Tl	Likely time needed to conclude a task	Table 8
Pessimist time	Tp	Pessimist time needed to conclude a task	Table 8
Optimistic time	To	Optimistic time needed to conclude a task	Table 8
Estimated time	Te	Estimated time needed to conclude a task	$\frac{To+4Tl+Tp}{6}$
Standard deviation	σ	A group of tasks standard deviation	$\sqrt{\frac{\sum_{i=1}^{n}(Tp_i-To_i)^2}{36}}$
Average time	μ	Average time to deliver the project	$\sum Te$
Time interval	X	Time interval to probability evaluation	Figure 7
Engineers overtime constant	Ke	Daily extra cost with project engineer team overtime	Table 5
Supply chain team overtime constant	Ks	Daily extra cost with supply chain team overtime	Table 5
Site team overtime constant	Ki	Daily extra cost with site team overtime	Table 5
Commissioning team overtime constant	Kc	Daily extra cost with commissioning team overtime	Table 5
Material cost	Cm	Project material acquisition extra cost	Costs according to the market
Engineers overtime cost	Ce	Extra cost with project engineer team overtime	$Ke * Overtime\ (days)$
Supply chain team overtime cost	Cs	Extra cost with supply chain team overtime	$Ks * Overtime\ (days)$
Site team overtime cost	Ci	Extra cost with site team overtime	$Ki * Overtime\ (days)$
Commissioning team overtime cost	Cc	Extra cost with commissioning team overtime	$Kc * Overtime\ (days)$
Risk extra cost	Cr	Extra cost for each risk occured	$Cm + Ce + Cs + Ci + Cc$
Total extra cost	Cr_T	Total extra cost of every risk occurred in the project	$\sum Cr_i$

Hazard probability	Ph	Hazard probability of occurring	Table 8
Random number	Nr	Auxiliary number for each iteration	0 to 1

3.1 Problem characterization

To characterize the problem, it is essential to define the project scope. This requires detailing the following information:

- The technical objective of the project and its application in an automaker production line, e.g., introducing a new car model in an automaker's production line.
- Assumptions to be considered in the scope definition, e.g., the new car model should not reduce the productivity of current models.
- Project requirements, e.g., the new production line process should be fully operated by robots.
- Project milestones, i.e., key stages and objectives of the project, e.g., the launch date of the new model.
- Production line layout.
- Human resources available for the project, e.g., mechanical engineers, electrical technicians, and site coordinators.

With the information provided above, the following outcomes can be achieved: (i) WBS; (ii) network diagram based on the PERT method, including the definition of the critical path; and (iii) baseline project schedule, i.e., the sequence of tasks to be executed during the project along with their estimated durations.

3.2 Preliminary hazards analysis and evaluation of the risk

Once the project scope is defined, the following inputs are useful: (i) baseline schedule, (ii) assumptions, (iii) requirements, (iv) list of human resources, (v) project cost baseline, and (vi) technical opinions from specialists. With this information, hazards can be identified using Preliminary Hazard Analysis (PHA) as a tool for risk assessment.

To perform the PHA, the following definitions should be established:

•Hazard: description of the event that follows the risk.

•Cause: the possible cause of the hazard.

•Consequence: definition of the type of impact, i.e., extra cost (impact on the project budget) or delay (impact on the project schedule).

•Probability: according to Table 2.

•Severity: according to Table 3.

•Risk: according to Table 4.

Table 2

Probability matrix (the classification is a proposal of this paper and adapted from PMI, 2018).

Probability	Classification
0 - 10%	Very low
10 - 30%	Low
30 - 50%	Medium
50 - 70%	High
90 - 100%	Very high

Table 3

Severity matrix (the classification is a proposal of this paper and adapted from PMI, 2018)

Conseq.	Very low	Low	Medium	High	Very high
Extra cost	Insignificant cost increasing	1% to 5% cost increasing	5% to 10% cost increasing	10% to 15% cost increasing	> 15% cost increasing
Delay	Insignificant time increasing	< 5% time increasing	5% to 10% time increasing	10% to 20% time increasing	> 20% time increasing

Table 4

Risk matrix (the classification is a proposal of this paper and adapted from PMI, 2018)

		Severity				
		Very low	**Low**	**Moderate**	**High**	**Very high**
Probability	**Very high**	Medium	Medium	High	High	High
	High	Low	Medium	Medium	High	High
	Moderate	Low	Low	Medium	High	High
	Low	Low	Low	Medium	Medium	High
	Very low	Low	Low	Low	Low	Medium

3.3 Evaluate probability

Once the critical path has been defined based on the network diagram (the output of step 1), it is necessary to identify which evaluated risks impact the tasks on the critical path. Given a critical path composed of n tasks, structured interviews with technical experts can be used to determine, for each task i, the pessimistic time to complete the task (Tp_i), the optimistic time (To_i) and the likely time (Tl_i).

Since a project is a unique endeavor, there is no database available that could provide the exact time needed to conclude each task. Therefore, a structured interview with specialists in BiW projects is a viable alternative to estimate the parameters related to time. The structured interviews were carried out with a project manager, a mechanical engineer, a control engineer, a supply chain specialist, and a site coordinator. The specialists were asked (i) what risks could impact possible delays on the specific task; (ii) if the risk occurs, what is the Tp_i for each specific task based on their previous experiences; and, at last, (iii) if the risk does not occur, what is the To_i and Tl_i for each task, taking in consideration their previous experiences and the Parkinson Law influence (Gutierrez & Kouvelis, 1991).

Hence, as presented by Slack et al. (2010) and applied by Barbosa et al. (2019), we use the beta distribution to calculate the estimated time (Te_i) (1) required to conclude each task. According to the central limit theorem, as more tasks are evaluated, the probability distribution for the project's completion time (as the sum of the times for all tasks) approaches a Gaussian curve (Montgomery & Runger, 2003). Using this data and adapting the equations provided by Montgomery & Runger (2003) with the PERT parameters, it is possible to compute the average time (2) and the standard deviation (3) for completing the project:

$$Te = \frac{To+4Tl+Tp}{6} \qquad (1)$$

$$\mu = \sum_{i=1}^{n} Te_i \qquad (2)$$

$$\sigma = \sqrt{\frac{\sum_{i=1}^{n}(Tp_i - To_i)^2}{36}} \qquad (3)$$

Once we have the average time to complete the project (μ) and the standard deviation (σ), we can assess the probability that the time required to finish the entire project in X days follows a normal distribution, parameterized by the mean (μ) and the standard deviation (σ).

The outputs of this section are: (i) a normal distribution to model the time required to complete the project in X days; and (ii) based on the structured interviews, the probability of the extra cost impact for each hazard (defined in step 2), with probabilities greater than "Very Low".

3.4 Evaluate consequences and impact

Given the hazards identified that have extra cost as a consequence, with severity classified as greater than "Low" we can calculate the financial impact of the risk's extra cost, Cr, according to (5). As can be seen in Table 1, that equation is developed in this paper and takes into consideration, for each risk, the material cost, according to the average market prices in Brazil in 2021 and converted from Brazilian Real to US Dollars, based on the 2021 exchange rate, Cm; engineers overtime cost, Ce; supply chain team overtime cost, Cs; site team overtime cost, Ci; commissioning team overtime cost, Cc. Although this paper uses Table 5 to define daily overtime costs for each role, this number could change depending on the region and the year.

$$Cr_j = Cm_j + Ce_j + Cs_j + Ci_j + Cc_j \qquad (5)$$

Table 5

Cost parameters (these values are proposals of this paper)

Parameters	**Symbol**	**Description**	**Value**
Engineers overtime constant	Ke	Daily extra cost with project engineer team overtime	US$220,04
Supply chain team overtime constant	Ks	Daily extra cost with supply chain team overtime	US$94,30
Site team overtime constant	Ki	Daily extra cost with site team overtime	US$377,21
Commissioning team overtime constant	Kc	Daily extra cost with commissioning team overtime	US$361,40

The output of this section is the establishment of a relationship between the probability and the extra cost for each of these hazards.

3.5 Quantitative risk assessment and risk categorization

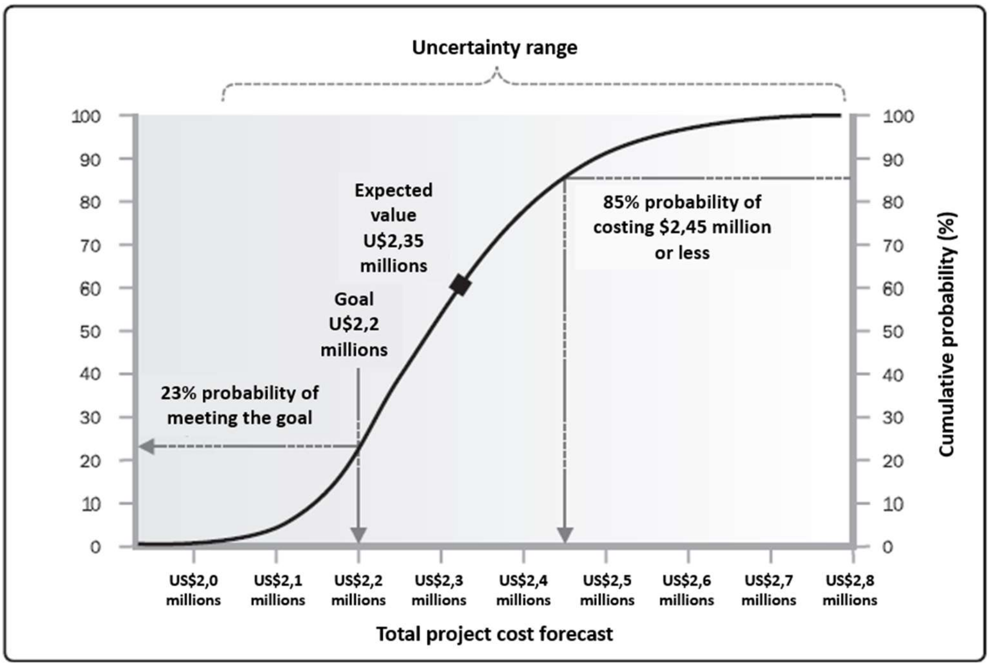
In this section, we use the mathematical model according to (6), as proposed by PMI (2018), to calculate the project's total extra cost (Cr_T), using the parameters mentioned in this paper. Cr_T Is the sum of the Cr_j for each risk j in a total of m occurred in a simulation.

$$Cr_T = \sum_{j=1}^{m} Cr_j \qquad (6)$$

In this paper, Monte Carlo simulation is used to forecast the risk impact on the project's baseline cost. Using this method, with the evaluation of consequences and impacts as inputs, it is possible to predict a range of probabilities for the project's extra cost.

In summary, to use the Monte Carlo simulation, we are using the following parameters: Cr; the probability of occurring a given risk j (Pr_j) and random number r ($Nr \sim Unif[0,1]$). Therefore, for each iteration, representing a possible scenario, here is the step-by-step: a Nr is generated for each risk assessed; if $Nr < Pr_j$ for the j risk, we add Cr_j to Cr_T according to (6). As a result, ten thousand iterations will be done, making, as an output, an S curve (Figure 3) (PMI, 2018) that compares Cr_T with its probability as a result of the Monte Carlo simulation.

Figure 3
PMBOK's S Curve



Source: Project Management Institute (2018).

In addition, to facilitate risk communication with stakeholders, this paper proposes a project risk categorization based on both probability and consequence dimensions, as follows:

- Critical risk (CR): >50% probability that the total extra cost will exceed 50% of the project's estimated cost.
- High risk (HI): >20% probability that the total extra cost will exceed 20% of the project's estimated cost.
- Low risk (LO): >10% probability that the total extra cost will exceed 10% of the project's estimated cost.
- Negligible risk (NE): <10% probability that the total extra cost will be less than 10% of the project's estimated cost.

Consequently, this methodology recommends the following actions based on the managers' profiles: conservative project managers should estimate a contingency considering an extra cost with a probability of less than 10%; moderate project managers, between 10% and 30%; bold project managers, between 30% and 50%; and the most aggressive project managers, above 50%.

4. RESULTS AND DISCUSSION

To illustrate the viability of the proposed methodology, we apply it in the real case of a Brazilian body-in-white production line project.

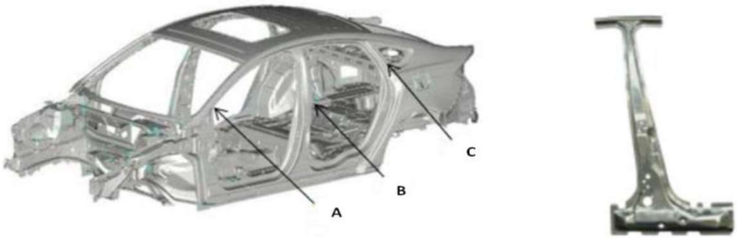
4.1 Problem characterization

The problem characterization in this paper is defined by the project scope, as outlined in section I. The scope applies to a BiW production line project in Brazil.

The project objective is to implement a robotic cell that enables automatic positioning, sealing, and welding of the B-pillar (Figure 4) of the inner bodyside on the outer bodyside of a new car model for a Brazilian automaker in the BiW stage.

Figure 4

The three main pillars in a car's body



Source: Design and Reinforcement of a B-Pillar (2017).

The milestones applied in the project were:

- Design review (i.e., the final approval of the 3D design for the automatic cell).
- Process validation (i.e., after the mechanical installation and commissioning of the fixtures and robots, the process is validated through an initial empty try-out).
- Pre-series (i.e., after process validation, the first B-pillar will be introduced for a loaded try-out to validate the product).
- Start of production (i.e., after the pre-series phase, production of the new model will commence for market release.).
- The project assumptions are:
- The milestones will not be moved forward.
- The B-pillar dimensions and mechanical properties are sufficient to withstand the process impact.
- Building a new production line will not be necessary; instead, the current line will be upgraded.

- The project team will receive the B-pillar, the current production line, and the precise dimensions of the outer bodyside.
- The project cost will be exempt from tax charges.
- There will be 48 hours per week allocated for the installation of fixtures and robots.
- During the installation of fixtures and robots, safety technicians will be present to support the team.
- The project requirements:
- The project and its implementation must adhere to the scheduled milestones and requirements.
- The production process to be implemented must be automated, utilizing minimal human resources.

As shown in the layout (Figure 5), the current production line (in blue) operates by loading the B-pillar onto the turntable (01). The robot (02), equipped with a gripper (03), transfers the part to the transport system (05), where the outer bodyside, already sealed, is positioned. Subsequently, robots (04 and 06) weld the two parts together, ensuring that both the B-pillar and the outer bodyside are securely joined.

To accommodate a new model, additional fixtures and robots will be installed (in orange). A new loading turntable (09), robot (07), and gripper (08) will be added. Additionally, the transport system (05) will be modified to support the geometry of the new part. Software modifications will also be made to robots (04 and 06), including a new welding program, and adjustments to the surrounding safety fence will be implemented.

Figure 5

BiW project layout

Source: Authors, 2024.

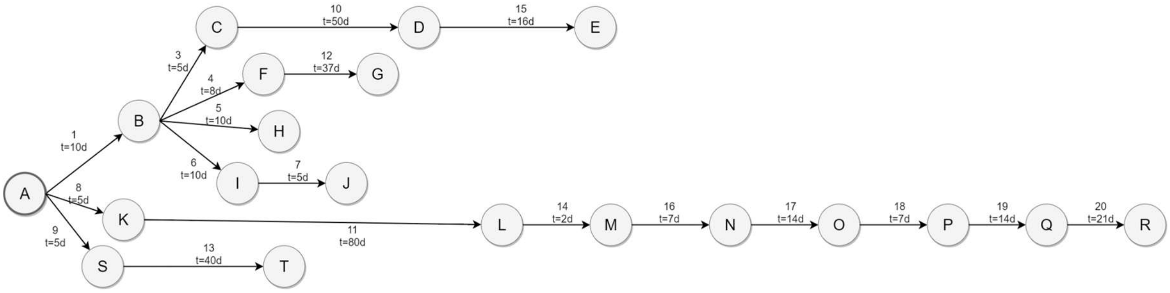
The work breakdown structure (WBS) should present the following deliverables:

- Engineering: The mechanical engineering team will design a 1000mm-high base to support the NJ290 – 3.0 robot. Additionally, they will design the gripper, turntable, transport system kit, and safety fences. For control engineering, the electrical, fluidic, and pneumatic systems, as well as the software, will be developed.
- Supply Chain: The supply chain team will issue purchase orders for all specified materials. They will also oversee manufacturing, supply, and logistics follow-up.
- Installation: The site team will be responsible for installing the mechanical components and making electrical and pneumatic connections.
- Commissioning: The commissioning team will upload the offline robot program, configure the welding software, and conduct I/O and trajectory tests. Their work will conclude after the loaded tryout during product verification.

The work packages outlined in the WBS are sequenced to create the network diagram shown in Figure 6, according to the PERT method. Through structured interviews with specialists, each task identified in the work packages will have a likely duration assigned. As illustrated, the critical path for this project is determined by the sequence of tasks 08-11-14-16-17-18-19-20, which are related to the acquisition and installation of the robots. The other paths are as follows: 01-03-10-15, related to the design, supply, and installation of the fixtures; 01-04-12, related to the electrical and fluidic project and material supply; 01-05 and 01-06-07, related to the development of the welding, PLC, and robot programs; and finally, 09-13, related to the specification, design, and supply of safety materials.

Figure 6

Diagram network – B-pillar new model



Source: Authors, 2024.

To ensure that the tasks are carried out according to the project schedule, the human resource distribution is as follows:

- Engineering: Five mechanical engineers, one electrical engineer, two process specialists, and one software engineer.
- Supply Chain: Two buyers, one supply chain engineer, and one logistics analyst.
- Installation: Four mechanical technicians, four electrical technicians, and two site coordinators.
- Commissioning: Two robot technicians, two software technicians, and two site coordinators.

The project cost baseline is built considering every hour spent by the human resources and the material acquisition. Thus, the total initial cost will be US$452,167.36 – the costs presented here were converted from Brazilian Real to US Dollars based on the 2021 exchange rate – and are divided into the project management, engineering, supply chain, installation, and commissioning costs:

- Project management: It was defined as 45 workdays to plan, advance control, meetings, and reports. Estimated cost: US$9,198.66.
- Engineering: It was defined as 78 workdays for the mechanical and automation projects. Cost: US$16,453.80.
- Supply chain: It was defined as 40 workdays for procurement. However, the main costs are located in the 2-robot acquisition (nearly €90,000.00 each); their grippers, turntables (up to US$27,500.00 and US$19,600.00 each), according to the steel kilogram cost, work hours for tooling and motor, sensors, cables, and hoses, costing over US$59,000.00, and material transportation (US$13,000.00). Estimated cost: US$399,846.67.
- Installation: It was defined as 22 workdays for the mechanical technicians, 24 workdays for the electrical technicians, and 23 workdays for the site coordinator. Estimated cost: US$17,328.06.
- Commissioning: It was planned for 8 workdays for the robot technicians, 9 workdays for the PLC technicians, 6 workdays for the site coordinator, and 4 workdays for the mechanical technicians. Estimated cost: US$ 9,340.17.

4.2 Preliminary hazard analysis and evaluation of the risks

The hazard identification and evaluation have been done through PHA (Table 6). Following the criteria presented in Section 3.2 and Figure 2, only the hazards with a probability greater than "very low" and a severity greater than "low" are presented.

Table 6

Preliminary hazard analysis

ID	Hazard	Cause	Conseq.	Prob.	Sev.	Risk
1	Process Validation milestone anticipation	Vehicle launch anticipation	Extra cost	Low	High	Moderate
2	Preseries milestone anticipation	Vehicle launch anticipation	Extra cost	Low	High	Moderate
3	Start of Production milestone anticipation	Vehicle launch anticipation	Extra cost	Low	High	Moderate
8	Fewer mechanical engineers available on the project than planned	Mechanical engineers allocated in other projects	Delay	Low	Moderate	Moderate
9	Fewer process engineers available on the project than planned	Process engineers allocated in other projects	Delay	Low	Moderate	Moderate
10	Fewer buyers available on the project than planned	Buyers allocated in other projects	Delay	Low	Moderate	Moderate
11	Fewer mechanical technicians available on the project than planned	Mechanical technicians allocated in other projects	Delay	Low	Moderate	Moderate
12	Fewer eletrical technicians available on the project than planned	Eletrical technicians allocated in other projects	Delay	Low	Moderate	Moderate
13	Fewer site coordinators available on the project than planned	Site coordinators allocated in other projects	Delay	Low	Moderate	Moderate
14	Fewer robot technicians available on the project than planned	Robot technicians allocated in other projects	Delay	Low	Moderate	Moderate
15	Fewer software technicians available on the project than planned	Software technicians allocated in other projects	Delay	Low	Moderate	Moderate
18	Fewer time available to install the fixtures on the field during the weekends	Production department demands the line to produce cars during the weekend	Extra cost, Delay	Moderate	High	High
19	Water and/or air not available on the weekend to make the tests	The factory needs to save energy during the weekends	Extra cost, Delay	Low	Moderate	Moderate
29	Steel cost significant increasing	Current economic scenario in the country	Extra cost	Moderate	High	High

30	Euro exchange significant increasing	Current economic scenario in the country	Extra cost	Moderate	High	High
38	Operation cycle time different from the robot program	Robots aren't fast enough to reach the cycle time and it's impossible to make the cycle anticipations as thought	Extra cost, Delay	Low	Moderate	Moderate
40	Toolroom supplier is overloaded	Toolroom supplier is allocated in others projects	Delay	Moderate	Moderate	Moderate
41	Delay on the materials needed to the robot manufacturing	Robot eletronic materials scarcity	Delay	Moderate	High	High
42	Delay on the robot importation due to red channel	Detailed documentation demanded for its importation	Delay	Low	High	Moderate
44	Delay on the eletrical materials due to red channel	Detailed documentation demanded for its importation	Delay	Low	Very High	High
54	Fixtures found with the wrong dimensions	Wrong machining process	Delay	Low	Moderate	Moderate
57	Sensor implemented doesn't realize the difference between the current and new pillar B	Both pillar B are very similar	Extra cost	Low	High	Moderate
61	Site coordinators overloaded with others project tasks during the installation period	Mistake on the tasks planning	Delay	Low	Moderate	Moderate
62	Installation period modification creates contractual fines with the human resources suppliers	Production department demands the line to produce cars during the weekend	Extra cost, Delay	Moderate	Moderate	Moderate
64	Turntable motor is underdimesioned and doesn't support its motion	Turntable weight underestimation	Extra cost, Delay	Low	High	Moderate
66	Virtual commissioning required to the project	Necessity to prevent greater impacts on current production line	Extra cost, Delay	Low	High	Moderate

4.3 Evaluate probability

Through structured interviews with specialists, the values for To_i and Tl_i were determined for each task in the critical path. Additionally, Tp_i was estimated by establishing a relationship between each task in the critical path and the hazards that impact those tasks (Table 7).

Using Table 7, we apply (1) to find Te_i each task in the critical path; (2) results in σ=6.69; (3) gives μ=192.50; and (4) is used to plot the Gaussian curve (Figure 7). This figure illustrates that, given X>192.50 days, there is a Y% probability of the project taking longer than X days. As shown, there is a 37% probability that the project will extend beyond 200 days.

Additionally, the probability of the extra cost hazards with severity greater than Low is presented in Table 8.

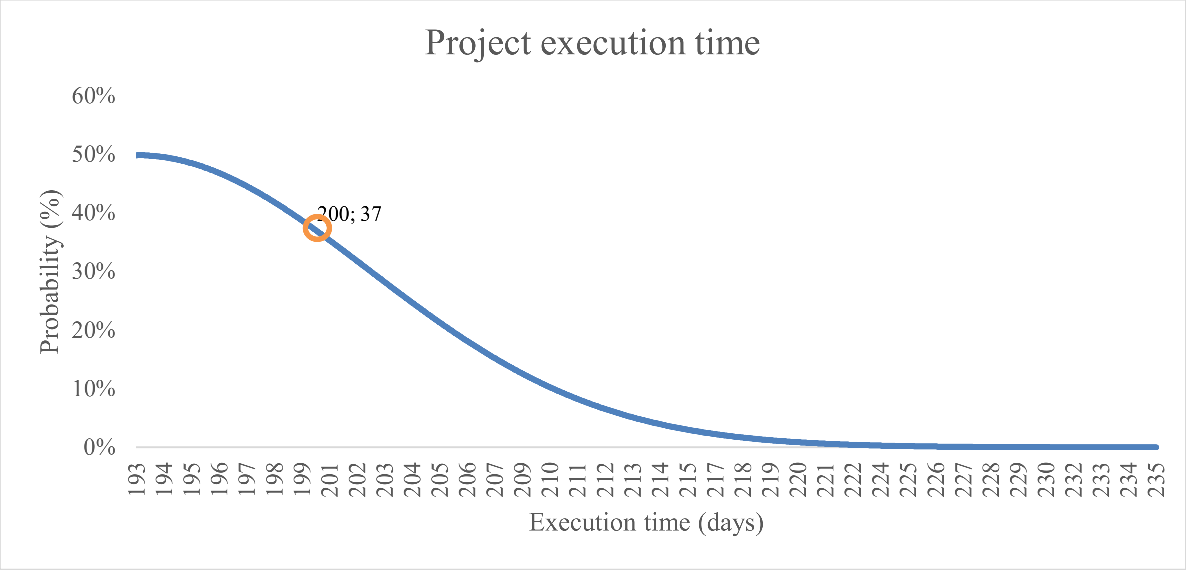
Table 7

Critical path tasks - pessimist, optimistic and likely time

ID	Work period	Task description	To	Tl	Tp	Pred.	Suc.	Hazards
8	Week-day	Robot specification	0	7	7		11	31
11	Week-day	Robots manufacturing	103	110	145	8	14	10, 16, 41, 42,
14	Wee-kend	Robot and its base installation	7	7	14	11	16	7, 11, 13, 17, 18, 60, 61
16	Wee-kend	Fence and safety materials installation	7	7	14	14;9	17	7, 11, 12, 13, 17, 18, 25, 49, 61
17	Wee-kend	Eletrical and fluidic installations	7	14	28	16	18	5, 7, 11, 12, 13, 17, 18, 25, 35, 36, 43, 56, 61
18	Wee-kend	Upload welding software, robot program, PLC and IHM	7	7	14	6;17	19	13, 14, 15, 17, 18, 23, 27, 28, 61
19	Wee-kend	Check robot installation and I/O tests	7	14	21	18	20	4, 7, 13, 14, 15, 17, 18, 19, 23, 27, 28, 37, 50, 61
20	Wee-kend	Empty and loaded tryout	9	16	37	19		4, 13, 14, 15, 17, 18, 19, 23, 27, 28, 32, 33, 34, 38, 46, 47, 51, 52, 57, 58, 59, 61, 64, 65

Figure 7

Gaussian curve – Pillar B execution time



Source: Authors, 2024.

4.4 Evaluate consequences and impact

In this section, we use Equation (5) to calculate the financial impact of the extra cost hazards with severity greater than Low (i.e., hazards 1, 2, 3, 18, 19, 29, 30, 38, and 57). By applying the estimated probabilities and calculating the extra costs, Table 8 is generated as the output for this section and will serve as input for the following one.

Table 8

Extra cost risks probability and impact

ID	Hazard	Cause	Prob.	Sev.	Risk	Impact	Prob.
1	Process Validation milestone anticipation	Vehicle launch anticipation	Low	High	Moderate	US$54,248.48	10%
2	Preseries milestone anticipation	Vehicle launch anticipation	Low	High	Moderate	US$54,248.48	10%
3	Start of Production milestone anticipation	Vehicle launch anticipation	Low	High	Moderate	US$54,248.48	10%
18	Less time available to install the fixtures on the field during the weekends	Production department demands the line to produce cars during the weekend	Moderate	High	High	US$45,207.07	40%
19	Water and/or air not available on the weekend to make the tests	The factory needs to save energy during the weekends	Low	Moderate	Moderate	US$22,603.53	15%

29	Steel cost significantly increasing	Current economic scenario in the country	Moderate	High	High	US$45,207.07	40%
30	Euro exchange significantly increasing	Current economic scenario in the country	Moderate	High	High	US$45,207.07	40%
38	Operation cycle time different from the robot program	Robots aren't fast enough to reach the cycle time and it's impossible to make the cycle anticipations as thought	Low	Moderate	Moderate	US$27,124.24	20%
57	Sensor implemented doesn't realize the difference between the current and new pillar B	Both pillar B are very similar	Low	High	Moderate	US$45,207.07	20%
62	Installation period modification creates contractual fines with the human resources suppliers	Production department demands the line to produce cars during the weekend	Moderate	Moderate	Moderate	US$27,124.24	35%
64	Turntable motor is underdimesioned and doesn't support its motion	Turntable weight underestimation	Low	High	Moderate	US$45,207.07	20%
66	Virtual commiosining required to the project	Necessity to prevent greater impacts on current production line	Low	High	Moderate	US$54,248.48	20%

4.5 Quantitative risk assessment and risk categorization

Given Table 8 as an input, the Monte Carlo simulation was executed, running 10,000 iterations. Each iteration represents a possible scenario of risks in which (6) was applied.

As a result, by correlating the sum of the extra costs for each iteration with the accumulated probability, the S curve was plotted (Figure 8). This graph can be interpreted as follows: there is a Y% probability of the extra cost exceeding X% of the baseline total cost.

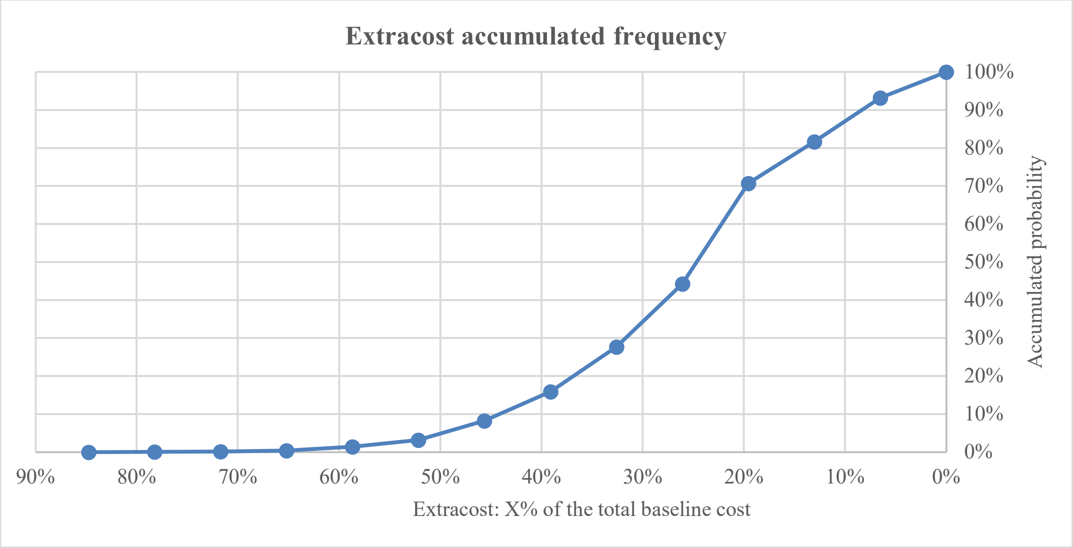
As shown in Figure 8, the risk categorization for this project is classified as HI (i.e., there is a >20% probability of the total extra cost exceeding 20% of the project's estimated cost). For instance, there is a 44% probability that the project's extra cost will exceed 26% of the baseline total cost, a 28% probability of exceeding 33%, and another 28% chance of surpassing 33%. The primary reason for classifying the risk as HI is the significant impact of hazards 18, 29, and 30.

In order to avoid significant losses in cost management, we recommend using an emergency reserve according to the risk tolerance of the project manager, as seen in Table 9. As shown, the level of risk tolerance is defined according to the proposed probability matrix (Table

2). Meanwhile, the recommended emergency reserve is calculated based on the predicted extra cost percentage at each accumulated probability (Figure 8).

Figure 8

S Curve – extra cost accumulated probability



Source: Authors, 2024.

Table 9

Risk tolerance

Risk tolerance	**Probability interval**	**Emergency reserve recommended**
Conservative	<10%	>US$199,623.40 (44%)
Moderate	10 - 30%	US$144,693.55 (32%) - US$199,623.40 (44%)
Bold	30 - 50%	US$111,532.25 (25%) - US$144,693.55 (32%)
Agressive	>50%	<US$111,532.25 (25%)

The advantage of the proposed methodology lies in its ability to evaluate the influence of each risk present in a BiW project and to quantify its impact on both the project schedule and budget within a probabilistic spectrum. This approach provides a comprehensive view of risk, allowing for a nuanced assessment of potential project outcomes under varying risk scenarios. However, a notable limitation is the potential imprecision in estimating both the probability of risk occurrence and the duration of each activity, due to the lack of a reliable database supplying these specific data points.

5. CONCLUSION

Through a real-world project, this paper proposes a methodology to perform a quantitative risk assessment of launching a new car in automakers' BiW production lines. The advantages found in this methodology are: (i) it takes into consideration the technical specificities of such types of projects to predict, in a probabilistic way, cost and time to deliver the project; (ii) it assesses, quantifies, and categorizes risks to recommend a financial contingency according to the project manager's level of risk tolerance; (iii) it allows the project manager to integrate risk assessment, risk communication, and risk management in the project's risk analysis. These advantages provide enough information to help project managers respond to the hazards in each project, allowing them to decrease risk impacts and increase the project's profit margin.

The main results found in its application were that: (i) there was a 37% probability of the project taking longer than 200 days to be completed; (ii) there was a 44% probability of the extra cost being above 26% of the baseline total cost, meaning the project is classified as HI risk; and (iii) a bold project manager should allocate between 25% and 37% of the baseline total cost as a contingency for the project. However, this paper limits its risk assessment to the impacts on time and cost of delivering the project.

The main limitations of this study include the lack of an assessment of risk impacts on the project's scope, safety, and quality; the absence of a sensitivity analysis; and limited exploration into the frequency determination for each risk. Additionally, a significant challenge lies in accurately modeling human behavior in adhering to the project schedule, particularly in line with Parkinson's Law.

Future research could benefit from assessing risks that may impact project quality, safety, or scope, as well as exploring strategies for risk communication and management. Additionally, an in-depth study of risk response strategies could significantly reduce the impact and likelihood of risks, thereby improving the project's financial performance and profit margins. This expanded focus on proactive risk management would offer valuable insights for optimizing project outcomes.

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