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A selection framework for derivative products: Development of an impact metric and platform value assessment methodology

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A SELECTION FRAMEWORK FOR DERIVATIVE PRODUCTS:

DEVELOPMENT OF AN IMPACT METRIC AND PLATFORM VALUE ASSESSMENT METHODOLOGY

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Abstract

In today's product development environment, most companies develop product platforms due to the time and cost advantages that are reaped on subsequent development efforts. Many Research and Development (R&D) efforts conclude with the establishment of a platform that anticipates certain technologies and/or markets. However, when a new unanticipated market or technology arises, firms often struggle to assess these opportunities. Most tools to date focus on the upfront decisions while the product platform is under development. There is little work that examines these decisions with the added constraint of a preexisting platform.

This work proposes a new methodology derived from existing tools that address platform development, specifically, the development of derivative products given the constraints of existing platforms and new opportunities that were not identified during the development of the original platforms.

The methodology estimates the impact of making a change in a specific part of the platform in order to integrate new technologies and develop new derivative products, using information theory and coupling indices that capture different aspects of a platform and are combined to extract the most relevant characteristics of each tool. This estimation is fed into a Real Options decision tree model that establishes the value of the opportunity conducting simulations for certain scenarios of markets to pursue, technologies to integrate, and existing platforms to use.

The methodology is applied to a water cooler in order to illustrate the process using two different platforms under a common set of assumptions. This case study suggested that the proposed approach facilitated the decisions to integrate new technologies and pursue new markets from existing platforms.

Opportunities for future work include examining the appropriate ways of combining Coupling Indices and Information Theory, the linkage between impact assessment and the cost of technology integration, and the relationship between the type of industry and the required investment to integrate technologies. In addition, a real application case would provide more meaningful results and allow the refinement of this approach.

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First, I want to acknowledge the work done by Jeanne Wesline, Matthew McLaughlin, and Carol-Lynn Goldstein in their thesis for the Master in Product Development at RIT because it was a starting point for my work and a clear guide in the literature review for this work.

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1 Introduction

Meyer and Lenherd [1] have defined a product platform as "a set of subsystems and interfaces that form a common structure from which a stream of derivative products can be efficiently developed and produced." Similar definitions of a product platform exist through much of the product development literature [2-4]. It has been well established, that product platform strategies give firms competitive advantages in the marketplace due to their ability to leverage existing platforms by rapidly introducing appropriate derivative products that meet new market demands. Dahmus et al. [5] highlight this and other advantages of developing product families over platforms, however, the product development literature typically focuses specifically on processes and tools to develop new standalone products and product platforms [6, 7]. Nevertheless, manufacturing firms must frequently both update and broaden their product lines not only to grow, but to survive as a company [8], but little attention is paid to the case in which a company wants to develop new derivative products from an existing platform based on information about new technologies and changes in the market. The company needs to decide which of these new opportunities to implement in one or more of its derivative products. Due to the competitive nature of the marketplace, these decisions need to be made quickly.

According to Wesline et al. [9, 10] corporations often have difficulties in determining the "best" derivative product(s) to develop from an existing product platform. "Best" means that the derivative product delivers optimal value to the corporation, which implies that it:

(1) is desirable to the market, and thus will generate revenue
(2) can be designed, produced and supported within the existing capabilities of the corporation
(3) aligns with the product strategy of the corporation

As a result, "best" derivative products will be unique to a particular organization.

Typical product platforms are complex and have many interactions between subsystems. As a result, when new features are added it will often require significant design tradeoffs along one or more performance dimensions to be made. Engineers and engineering managers need tools and methods that allow them to evaluate these tradeoffs early in the design process so that they can optimize the value delivered to the end user and to the company.

Given knowledge of either new technologies or new market opportunities, the decisions would include but would not be limited to:

(i) what changes in a platform does the market-place value?
(ii) which platform should be changed?
(iii)is it better to develop a new platform in order to respond correctly to the market?

The product development literature describes numerous tools to help facilitate these decisions. Alizon et al. [11, 12] describe some studies on redesign of a family of products "focusing on various aspects such as modularity, cost, and commonality/diversity." Khadke and Gershenson [13] explore the technology change to plan the product platform designs, but no comprehensive framework has been documented that deals specifically with unplanned derivative product development. A major objective of this research is to develop a method to analyze alternative derivative products given the constraints of a preexisting product platform.

The first attempt to address this problem proposed a selection framework with four main elements: Platform Characterization, Market Characterization, Technology Evaluation, and Concept Generation & Initial Filtering [9, 10]. An overview of the framework can be seen in Figure 1.

Market Characterization entails understanding customer requirements, customer priorities and market opportunities, and which potential markets that a derivative product could serve. Platform Characterization involves gathering important characteristics pertaining to the existing product platform. Technology Evaluation focuses on potential new technology opportunities available to the company and specifically how they could be incorporated into the platform and what impacts it will have on the platform. Concept Generation and Initial Filtering is a twofold activity to develop an exhaustive list of derivative concepts and subsequently reducing this large set of opportunities to a more manageable subset.

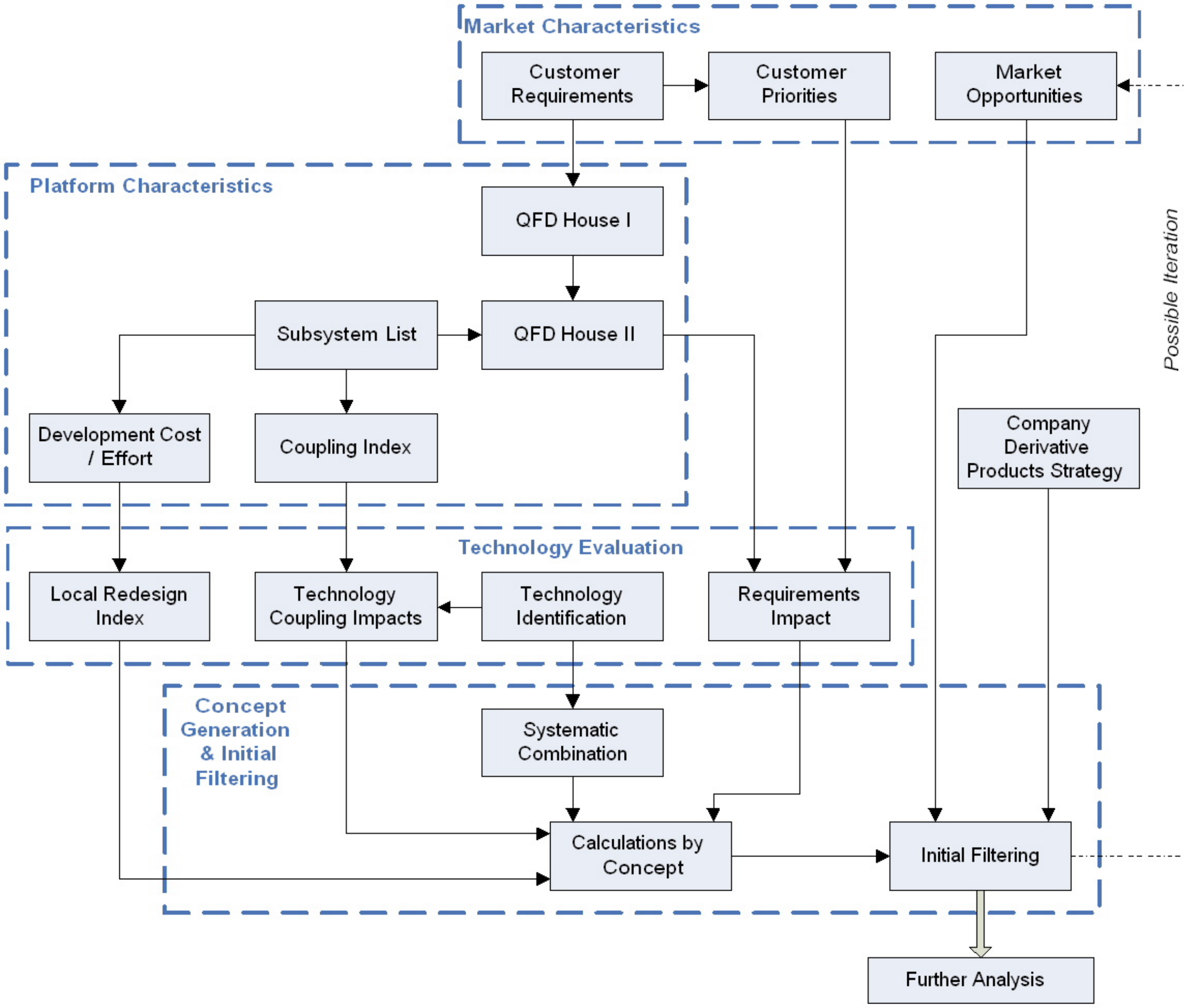


Figure 1 Framework Overview [10]

This attempt provided some insights into the nature of the problem, however elements of the process were cumbersome and improvements were needed to make the process more useful product development decision-makers. One area that was identified as an opportunity for improvement was the measurement of impact. It is believed that if a robust impact metric, which is linked to the modularity of the product, is used in the framework, the assessment process would be greatly simplified. Another shortcoming that was identified was the assessment of the value of these opportunities.

To respond to these drawbacks, the assessment should account for maximum satisfaction of market needs, while minimizing the effort to develop and deliver those derivatives. In order to fulfill that objective, the following must be accomplished:

i. Metrics need to be identified or developed that characterize the value that will be delivered to the marketplace by a particular product derivative.

ii. Metrics need to be identified or developed that correlate to the costs and effort that will be required in order for the derivative product alternative to be developed.

iii. A prescriptive methodology that will aid product development practitioners with implementing these metrics to guide their decision-making needs to be developed.

It is the goal of this thesis to address these objectives. In Chapter 2 the problem is defined. Chapter 3 presents a literature review that examines the product platform literature and also explores different approaches to measure modularity and different approaches to assess the value of products and product platforms, which are both key elements of a successful framework.

In Chapter 4 a selection framework is proposed, which incorporates new metrics of the impact of a change to a given component within a platform and the assessment of the value of a specific scenario; in Chapter 5 the methodology is illustrated with an application case that clarifies the details of the assessment.

The thesis concludes with a discussion of the results in Chapter 6 and the conclusions and future work are summarized in Chapter 7.

2 Problem Statement

As was discussed in the last section, companies struggle to respond to new technologies and new market opportunities. These decisions can be made more difficult when the added constraint at a preexisting platform is considered which may limit the redesign options available to the product development team. The task to generate a new product may require the selection of the appropriate platform to develop the new derivative product, adapt the existing platforms or even generate new platforms; clearly, this is not an easy task.

However, one thing is certain, the new technologies or market opportunities that are identified would affect (change) some aspects of the platform. Ultimately components, interfaces, and /or processes change due to the integration of the new technologies. The impact of these decisions should be analyzed and compared against the value that the new opportunity offers to the company in order to determinate the action to pursue.

In order to assess the impact of the changes to a given platform a metric should be developed that captures the different aspects of the architecture and the strength of the relationships between modules or components. Having this information would facilitate the evaluation of how easy it is to change one element of the platform.

The value of the alternative should be estimated considering the risk and possibilities for the platform. This means that different scenarios should be considered to obtain a realistic idea of the benefits that could be extracted with the technology integration in a given platform.

The purpose of this thesis is then, to leverage existing tools and methods in order to facilitate the decision process in the integration of new technologies into existing platforms allowing the firm to develop new derivative products to pursue new market opportunities.

3 Literature Review

In today's highly competitive landscape, manufacturing firms must frequently both update and broaden their product lines not only to grow, but to survive as a company [8]. Firms cannot afford to make every product an independently-developed entity. Such firms would incur high costs due to redundancies in most areas of the business including engineering development effort, manufacturing inventory, service and sales force training. Product platform development has evolved out of the necessity to avoid these redundancies. The use of a product platform as the base for a series of derivative products has become commonplace in many of today's fast-paced companies. These companies have recognized that the development of derivative products from a platform can mean significant savings in both time and resources. Derivative product projects can save from 50% to 90% in comparison to creating non-platform products that fulfill the same market needs [3].

Platform planning has been discussed in terms of distinctiveness and commonality [2-4, 8, 14]:

> "Planning the product platform involves managing a basic trade-off between distinctiveness and commonality. On the one hand, there are market benefits to offering several very distinctive versions of a product. On the other hand, there are design and manufacturing benefits to maximizing the extent to which these different products share common components." [3]

This planning process entails the development of three distinct plans, the product plan, the differentiation plan, and the commonality plan. The product plan describes the derivative products from the platform over time, identifying the market segments to be served by each. The differentiation plan calls out the "differentiating attributes" (or DAs) and indicates how these vary across the derivative products. The commonality plan lists the subsystems (or "chunks") of the platform architecture and defines the extent to which these subsystems are shared through the series of derivative products. Once these plans are in place, design engineers can identify where trade-offs might be necessary. While these plans would be useful in generating ideas for derivative platform products, they would only provide qualitative guidance for evaluating and ultimately selecting promising product alternatives.

Despite the advantages of derivative products, inevitably unanticipated technologies will be developed and unanticipated market segments will emerge. While these unanticipated changes may not have been accounted for in the initial development of a product platform, tools and methods are still needed that allow engineers and engineering managers to evaluate how to best accommodate these changes within the existing product platforms. Thus quantitative measures are needed.

The two broad areas that need to be quantified in order to evaluate the incorporation of changes into a platform are (1) the cost of the alternative, (2) the benefit of the alternative. The cost of the alternative will be related to the difficulty of implementing the alternative, which is linked to the modularity of the architecture. The benefit of the alternative is linked to value that will be delivered by the alternative. The following section summarizes the literature in these two areas.

3.1 Modularity Measures

Central to development of quantitative tools for product platform development is the concept of modularity. The modularity of an architecture is the degree to which the product functions are implemented by the physical elements, or "chunks" of the product [3]. In the ideal, a completely modular architecture would have a 1:1 map between a single function and a single "chunk" of the product [3]. Nevertheless, Gershenson et al. [15, 16] showed how wide the term can vary and how there is no consensus in the literature on which is the best way to measure the modularity of a product or a platform.

Furthermore, there are cases when modular architectures are not appropriate [17], but a key benefit of fully modular designs in which all interfaces are completely defined and static, is that a change to a module should not cascade throughout the product and influence other functions, thus a strategy of developing modular architectures is a promising means for firms to manage the complexity associated with developing these products. Other relationships between modularity and costs have been explored which are focused on the different life-cycle stages of a product [18, 19] and there does not seem to be a clear relation between the modularity in the different stages of the life-cycle and the costs.

An approach to measure the modularity of a product would be to establish the number of standard components (elements or subsystems) by level. If the product has a large number of standard components compared to unique specific components, then it would be easy to interchange or substitute those with similar products within the same platform or family of products. Mikkola and Gassmann [20] propose a measurement of the modularity with an index that represents the component composition of the product architecture that can be extracted from the BOM (Bill of Materials) for the product:

$$b = \frac{n_{NTF}}{N} = \frac{u}{N}; \quad 0 \le b \le 1 \tag{1}$$

Where

u: Number of New-to-Firm (NTF) components

N: Total number of components

N-u: Number of standard components

b: representation of the modularity of the product going from a perfect modular architecture (b=0) to a perfect integral architecture (b=1).

The same concept can be used to evaluate the modularity of the products by level, considering the components as standards if they are used in several products or platforms within the company. In this way, we would get a general index b_0 that represent the modularity of the product, and indices b_1, b_2, b_n for the subsystems of the first level, b_{11}, b_{12}, b_{1m}, for the second level of the first module, and in this way evaluate the entire product at the desired level of detail.

$$\begin{aligned} b_n &= \frac{n_{NTF_n}}{N_n} = \frac{u_n}{N_n}; \quad 0 \le b_n \le 1 \\ b_{nm} &= \frac{n_{NTF_{nm}}}{N_{nm}} = \frac{u_{nm}}{N_{nm}}; \quad 0 \le b_{nm} \le 1 \end{aligned} \tag{2}$$

where,

u_n: Number of New-to-Firm (NTF) components in the subsystem n of the product.

N_n: Total number of components of the subsystem n.

N_n-u_n: Number of standard components in the subsystem n.

b_n: representation of the modularity of the subsystem n.

u_{nm}: Number of New-to-Firm (NTF) components in the subsystem m of the subsystem n.

N_{nm}: Total number of components of the subsystem m.

N_{nm}-u_{nm}: Number of standard components in the subsystem m within the subsystem n.

b_{nm}: representation of the modularity of the subsystem m within the subsystem n.

This approach does not take into consideration the relations between the modules in the system. It is more a measure of the standardization of the product than the modularity of the system. Similar metrics assess the commonality or diversity of a family of products, and many of those were reviewed by Alizon et al. [21, 22] and Fixson [23]. To actually measure the modularity there is a need to evaluate the connections between components, sub-modules, and modules.

A different approach was proposed by Wang and Antonsson [24, 25] that uses Information Theory, specifically Minimum Description Length, to describe the modularity of a system. This approach captures the layers and boundaries of the modules that the elements have to cross in order to interact with the rest of the system as well as the number of interactions, both relevant aspects for an estimation of the impact of changing an element in a platform. The method consists of evaluating the system in terms of connections; each connection or interaction between the module and other component, between modules (inter-module), or inside the modules (intra-module) of the system would be quantified by the length of a message that would describe each link.

In the end, all of the message lengths of the system are added and compared against the length of the messages of the system if no modules were defined as follow:

$$M_d = \frac{L_o - L_d}{L_o} \quad (3)$$

where,

M_d is the modularity of the system

L_o is the length of the message for the system with no modules

L_d is the length of the message for the system with the configuration that is under analysis.

The index, M_d, would be an indication of the reduction of information flow through the use of modules being 0 equal to the original system.

The method encodes graph structures that represent the system including three types of information: Units (components or sub-modules), Links (connections between different units), and Interfaces (means of interaction for a unit inside one module with another unit outside the module). With this information a message is created in the following way:

1. The whole graph is a unit.
2. Unit = Name tables + list of Links.
3. Name tables = Names of units and interfaces which are visible in the level.
4. Link = Name of two vertex units + attributes.
5. Name of vertex units could be <Node> or <SubMod M_1> <M_1's SubMod>… <M_i's SubMod> <Interface in SubMod M_i>.

The interfaces are just a unit that relates with another unit outside the module. Now, to quantify each of the links let us estimate the length of the message for the names of the links.

Let $L^{(n)}_j$ be the name length of node j, $L^{(m)}_j$ be the name length of sub-module j, $L^{(o)}_{jk}$ be the name length of interface k of sub-module j. Then the message length for names of links (name tables) in the module is:

$I^{(nk)}$ = Sum of the lengths of all links in the module

$$I^{(nk)} = \sum_{j=1}^{N^{(n)}} L_j^{(n)} \times N_j^{(n)} + \sum_{j=1}^{N^{(m)}} L_j^{(m)} \times N_j^{(m)} + \sum_{j=1}^{N^{(m)}} \left(\sum_{k=1}^{N_j^{(o)}} L_{jk}^{(o)} \times N_{jk}^{(o)} \right) \quad (4)$$

where:

- $N^{(n)}$: number of single nodes.
- $N^{(n)}_j$: number of links connected to node j.
- $N^{(m)}$: number of sub-modules.
- $N^{(m)}_j$: number of links connected sub-module j.
- $N^{(o)}_j$: number of interfaces of sub-module j.
- $N^{(o)}_{jk}$: number of links connected to interface k of sub-module j.

Then the length of each label can be estimated as – log (p_j) where p_j is the frequency of the optimal length of the label and respond to:

$$p_j = \frac{N_j}{\sum_{j=1}^{N_i^{(u)}} N_j} \tag{5}$$

then, the total encoding length for a unit label is:

$$-\sum_{j=1}^{N_i^{(u)}} N_j \log(p_j) = -\sum_{j=1}^{N_i^{(u)}} N_j \log\left(\frac{N_j}{\sum_{j=1}^{N_i^{(u)}} N_j}\right) \tag{6}$$

The message at a specific level would be:

$$I_n^{(n)} = \sum_{all\ \mathrm{mod}ules\ at\ level\ n} I^{(nk)}$$

$$I_n^{(n)} = -\sum_{all}\sum_{j=1}^{N_i^{(u)}} N_j \log\left(\frac{N_j}{\sum_{j=1}^{N_i^{(u)}} N_j}\right) - \sum_{all}\sum_{j=1}^{N^{(m)}}\left(\sum_{k=1}^{N_j^{(o)}} N_{jk}^{(o)} \log\left(\frac{N_{jk}^{(o)}}{\sum_{k=1}^{N_j^{(o)}} N_{jk}^{(o)}}\right)\right) \tag{7}$$

An illustrative example of the application of this method is developed in section 4.2.

Modularity has also been associated with the way to handle the complexity of a structure or product. Numerous measures are used to describe product complexity. Hölttä and Otto [26] review various complexity measures described in the literature including structural complexity, architecture complexity, and module I/O complexity. It is pointed out that "all [of these complexity measures] treat any relation [to other components or modules] as having the same difficulty, which is not generally the case" [26]. The authors go on to describe a redesign effort complexity metric that aids in developing architectures that are flexible as viewed from the perspective of the redesign effort required.

A common tool used in architecture analysis is the Design Structure Matrix (DSM) introduced by Steward [27]. In a DSM, the subsystems or components of a given system are compared to one another in a matrix to establish the relationship between them. Typically, the columns represent the flow of information that the components supply and the rows represent the information that the components receive. These connections are usually expressed in binary

form and relate to physical connections, mass, energy, or information flows [28]. This tool has also been used for planning of team interactions in a product development process, an example is shown in Figure 2 of a DSM that combines the relationships between components and the team interactions[29].

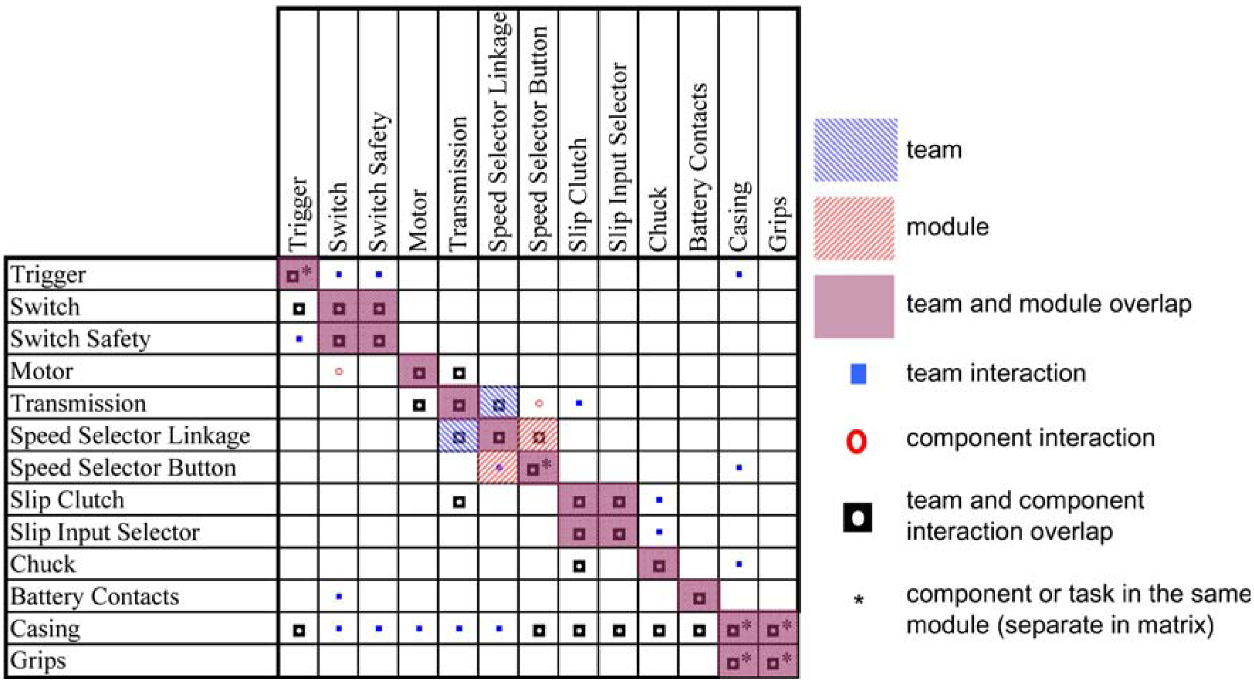


Figure 2 Combined component and team interaction DSM [29]

An interesting application of the DSM matrix has been used to identify not only the direct relationships between subsystems and components, but their indirect relationships as well [30-32]. In this way, the propagation of change can be traced through the system and with the definition of metrics for combined likelihood, and risk, the combined impact of a change can be determined.

Hölttä and de Weck [33, 34] introduced the Singular Value Modularity Index (SMI) and the non-zero fraction of the DSM as modularity measures. The SMI is derived by examining the decay rate of the sorted, normalized singular values of the DSM. An advantage of the metrics they derive is that there is no need to have the module boundaries defined to calculate the metrics. However, these measures address the modularity of the entire product and are not suitable for assessing the impact of the integration of a particular technology unless a certain measure of change in modularity can be determined.

$$NZF = \frac{\sum_{i=1}^{N}\sum_{j=1}^{N} DSM_{ij}}{N(N-1)} \tag{8}$$

$$SMI = \frac{1}{N}\arg\min_{\alpha}\sum_{i=1}^{N}\left|\frac{\sigma_i}{\sigma_1} - e^{-[i-1]/\alpha}\right| \tag{9}$$

Smaling and de Weck [28] develop the Technology Invasiveness (TI) Index, comparing the DSM of an original system and the DSM of a concept developed to infuse a technology into the system, to create a Delta DSM that is later analyzed for eight types of change, counted, weighted and combined into the TI index. One drawback of this approach is how to establish the weights of each type of change.

$$TI_i = \sum_{j=1}^{8} w_j \sum_{k=1}^{N}\sum_{l=1}^{N} \Delta DSM_{j,k,l}^{i} \tag{10}$$

Guo and Gershenson [35] developed another modularity metric that determines the internal (intra-module) and external (inter-module) relationships of the modules, adding the dependencies between components inside/outside the module and compared that to its size. The dependencies can be extracted from the DSM.

$$Modularity = \frac{1}{M}\left(\sum_{k=1}^{M} \frac{\sum_{i=n_k}^{m_k}\sum_{j=n_k}^{m_k} R_{ij}}{(m_k - n_k + 1)^2} - \sum_{k=1}^{M} \frac{\sum_{i=n_k}^{m_k}\left(\sum_{j=1}^{n_k - 1} R_{ij} + \sum_{j=m_k+1}^{N} R_{ij} \right)}{(m_k - n_k + 1)(N - m_k + n_k - 1)} \right) \tag{11}$$

Martin and Ishii [36, 37] introduced the Coupling Index as another way to evaluate the relationships in the system. The coupling index analyzes the strength of each connection in a matrix similar to the DSM. Each cell captures the specifications that supply information from the components in the columns to the components in the rows and evaluates the sensitivity of the component to a change based on the following scale:

Table 1. CI Rating system for sensitivity [36]

Rating	Description
9	Small change in specification impacts the receiving component (High Sensitivity)
6	Medium High Sensitivity
3	Medium Low Sensitivity
1	Large change in specification impacts the receiving component (Low Sensitivity)
0	No specifications affecting component

3.2 Value Measures

The value of an alternative is based on the customer response to the product. In order to capture the customer perception of the product the Quality Function Deployment (QFD) is a widely used technique, however it is hard to extract quantitative measures of that perception and to translate them into design features that maximize the value.

The Kano Model is a concept for categorizing product features or attributes in terms of customer satisfaction levels. Product attributes can be designated as one of three types: "dissatisfiers," "satisfiers," and "delighters." "Dissatisfiers" can be described as attributes that are necessary to the product. If the product is delivered without these, the customer will be dissatisfied with the product. "Satisfiers" result in customer satisfaction when present in the product, and dissatisfaction when not present. For these attributes, improvements along customer-identified performance metrics can increase customer satisfaction. The absence of "delighters" does not result in dissatisfaction because the customer is not really expecting them to be there, but if some delighters are included in the product, customers are usually pleased, and as a result, the product should be very successful. A competitive strategy for the product should account for all three types of attributes when defining feature sets. According to the model, over time, the delighters shift to satisfiers, and satisfiers shift to dissatisfiers [38, 39].

Meeting customer requirements is not enough to capture and retain market share. Products need to contain desirable qualities and customer expectation and satisfaction should be exceeded. Combining Kano model analysis and the technical correlation matrix involved in QFD can have significant positive effects on attractive quality creation and product innovation [38].

Thurston et al. [40, 41] proposed the use of Multi-attribute Utility Functions to establish the value or utility of a product. It relates the performance of the product in certain parameters with the utility that a customer may perceive by the product; that could be related with the success of the product in the market. Each variable (extracted from the house of quality of the QFD – Quality Function Deployment) requires a utility function that would determine how *good* the design of the product is. In the end a total utility for the product can be calculated.

In addition to the value of the product to customers, products need to be evaluated in terms of financial value to the firm. Marketing and finance organizations use value metrics such as Return on Investment, Net Present Value, Real Options, and Expected Commercial Value, along with sensitivity analysis around these metrics, to measure the value of a new product [42].

Return on Investment (ROI) is one method for gauging the success of a product, but it requires a large quantity of information. In order to calculate ROI, one needs to know how many of a particular product will be sold, the expected price of the product, and its development and manufacturing costs. These pieces of information are usually not available (or not fully accurate) until late in the product's development, or even after product launch. As a result, this metric is not appropriate for use during the early concept generation and selection phases [42].

According to Cooper [42], a portfolio of products may be managed by ranking the products that are being considered for development by their prospective Net Present Value (NPV). There are some problems with using this formula. One such issue is that the financial information is merely a projection of what is perceived to occur in the future, a downfall shared by ROI. This projection does not necessarily reflect what will actually come to pass. In addition to this shortcoming, NPV does not take into account strategic considerations, and it ignores probabilities of risk and success [42]. Even with the application of discount rates, NPV can only account for uncertainty on the downside, or "the possibility that actual cash flows may be much lower than forecast" [43].

Expected Commercial Value (ECV) is another metric used to place a value on a prospective project. ECV differs from NPV as it considers future earnings from the project, the probabilities of both commercial and technical success, and both commercialization costs and development costs. Once the ECV is calculated, a Monte Carlo simulation can be used to simulate risk profiles for the uncertain inputs [42].

Another method for measuring financial value is Real Options Analysis (ROA). Real Options adapts the mindset and tools of financial options in considering business opportunities. Unlike discounted cash flow techniques like NPV, ROA recognizes that projects do not follow a predetermined path to a predetermined outcome. Rather, there are often unplanned events that occur during a project's life, and there are also opportunities to change the project plan [44].

ROA regards the execution of a project as a "sequence of major decisions" [45]. At certain points in the project life-cycle, management can choose to continue funding to meet the original launch date, increase funding to speed up development, postpone the continuation of the project until a later date, or even cancel the project entirely. These decisions are made based on reevaluation of the market and technical risks. The evaluation of ROA accounts for the costs and benefits of each of these possibilities [44-46]. Since the real options approach involves future decision-making, it cannot simply be calculated once at the outset of a project. It requires that managers implement "an adaptive approach that monitors the resolution of future uncertainties" throughout the project life-cycle [47].

ROA implies that the risks of the project, rather than being avoided, should be examined to find "options" that could maximize the rewards for the system. De Neufville [48] discusses this aspect of ROA and states that "the act of seeking out risks can be difficult for designers to accept… it may be culturally difficult to persuade designers to look at risky situations as opportunities to develop real options that will add value to the overall performance of the system". By looking at those risks the company can manage better the uncertainties with a proactive attitude instead of a classical reactive analysis where the estimates are made for a given scenario.

This technique is particularly beneficial for development activities and flexibility in timing [48], this includes the assessment of R&D projects, and the product development processes that may result from these, helping to find the optimal moment to launch a certain product, introduce a variant in the market, or perform upgrades in the system or its modules.

As Kalligeros et al. [49, 50] discussed, the major uncertainties that are evaluated in product development are the response of the market, and the non-diversifiable parts of the products. The later would imply a higher risk because it constrains the response of the entire platform of products to the market, therefore the ROA should be used to evaluate the different options in the design looking for more flexible platforms that allows more derivative products.

Gonzalez-Zugasti et al. [51] commented on the application of the Real Options on development projects: "When investing into a real asset, such as a development project, an initial investment needs to be made. Usually this is a small investment compared to the investment that

will be made in the future to commercialize the resulting product. A real option exists because the firm has the choice to drop the project and not make the commercialization investment if the development goes poorly or the market situation changes. In that case the only loss incurred is the initial investment" [51].

Faulkner [47] as well as Gonzalez-Zugasti et al. [51] introduced the decision trees as the way to model the different alternatives of the product development process, recognizing that this is a very time consuming technique but appropriate for simple and fairly complex cases. Faulkner also points out that the problem with discounted cash flow (DCF) methods "is the mindset that has developed around it" [47].

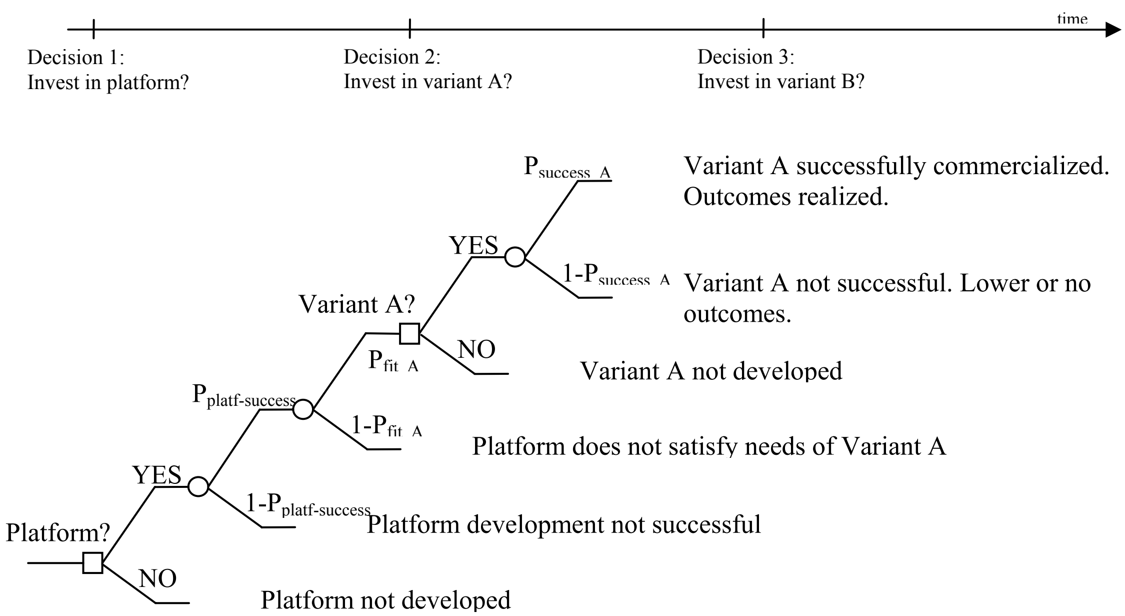


Figure 3 Generalized platform-based product family development [51].

However van Putten and MacMillan et al. [43, 52] suggest that the DCF is appropriate for projects with low uncertainty and that the tools are not mutually exclusive, instead the DCF and ROA should complement to allow managers to make better decisions. It is pointed out that Real Options should not become a way to justify every project and that analysis only make sense if the project can be terminated early at low cost if things don't go well, "fail fast, fail cheap, move on" [52]. They also highlight that there is a difference between the uncertainty about the

revenues and the uncertainty about the costs which tend to be higher than you expect and therefore should decrease the value of the project. With all these considerations they propose the following way to value an option:

$$\underset{\text{total project value}}{TPV} = \underset{\text{net present value}}{NPV} + \underset{\text{adjusted option value}}{AOV} + \underset{\text{abandonment value}}{ABV} \qquad (12)$$

Jiao et al. [53] propose the application of the real options to the product family design with the following equivalencies:

Table 2. Equivalencies in real options application [53]

Stock call option	Real Option	Product Family Design
Current Value	(Gross) present value of expected cash flow	Expected profit
Exercise Price	Investment cost	Design flexibility index Process flexibility index
Expiration time	Time until opportunity disappears	Time to Market
Expected rate of return on the asset	Risk-free interest rate	Customer unsatisfactory risk Process deficiency risk
Volatility of the asset (Probability)	Project value uncertainty	Uncertainty of customer needs

They also point out three major characteristics of real options methods:

1. Flexibility: The holder of the option has the right but not the obligation.
2. Uncertainty: Exercise the option only if the price increases.
3. Irreversibility: the right ceases when the option is exercised.

De Neufville and Wang [54] explored the real options “in” projects identifying two classes of options that have value due to flexibility: Those with the value of timing in which the time of implementation is crucial to maximize revenues or minimize losses; the other type is the one that has the value of Flexible Design, in which the design could change according to the realization of uncertain variables. In both cases the options exist because there is uncertainty in the project and only by having flexibility there is a real chance of getting advantage of the situation.

Related with the flexibility in product development is the modularity. Modularity is a way to maintain the flexibility in a product or a platform of products, therefore “A modular product can be viewed as a portfolio of options to upgrade” [55].

In order to calculate the value of an option there are several approaches, the most significant according to Amram and Kulatilaka [55] are:

- The solution of a Partial Differential Equation (PDE) in which the most used is the Black-Scholes equation,
- Dynamic Programming that can be implemented through a binomial model, and
- Simulations through the Monte Carlo method.

3.3 Research Opportunities

Having reviewed the literature in these areas it seems clear that there are opportunities to contribute in order to facilitate the decisions involved in the integration of new technologies into existing platforms that allow the firm to develop new derivative products responding to unanticipated markets. Some of the possible contributions would be:

- Develop a metric that captures not only the quantity of interactions in a product but also the strength of those interactions and that can be applied at a component level if desired.

- Develop a metric that accounts for the contribution of each one of the elements to the impact metric as a result of changes.

- Estimate the value of an alternative of technology integration having defined a scenario of certain markets to pursue and possible platforms from which a derivative product can be developed.

- Relate the impact assessment with the value estimation of the scenario in order to streamline the decision process.

4 Decision Framework

The end goal of this work is to provide firms with tools to make better decisions with regards to derivative product development projects that involve changes to a platform that was already developed. This involves minimizing the effort (and consequently the cost) to implement the changes while maximizing the value of the new opportunities. This activity generates alternative derivative product concept(s) for the firm to pursue.

Such a framework could be useable by firms as a means of:

1. Generating derivative product concepts by understanding and making use of newly available technology and, seeking newly identified market opportunities
2. Sorting, ranking, and screening derivative concepts based on appropriate metrics, assessing risk, value, and other appropriate measures, and developing a subset of concepts that are most attractive to the firm.
3. Selecting the best product concept to pursue using a final evaluation strategy to select from the high value derivatives.

4.1 Overview of the Methodology

Given the two scenarios mentioned before of having a new technology available or a new market segment identified for a derivative product of the platform, the result is the same: A new opportunity has been discovered and needs to be assessed. The proposed framework includes five phases where the opportunity and the platform are characterized in order to evaluate the changes and then generate and select the best concept for a new derivative product where the value of the opportunity exceeds the cost of its implementation. This is not very different from a generic problem solving methodology where first the problem is identified, the alternatives are generated, analyzed and finally a decision is made on the solution to implement. The key step is the analysis of the alternatives because the decision depends most heavily on the quality of this step.

A more detailed version of this process is shown in Figure 4 and is discussed below.

The first phase is to identify potential technologies and markets that were not considered at the time of the development of the platform or were not available. This stage would develop a

better understanding of the value of the opportunity through the customer requirements and the review of the available platforms that the firm has that may fit the needs.

Alternatives Generation involves the systematic exploration of the identified technologies, markets and platforms to produce a set of alternatives to pursue. Some of those alternatives may not be feasible therefore a preliminary screen should be conducted in order to continue with the analysis of only the most promising alternatives.

The stage of Alternatives Assessment is the core of the analysis and the focus of this thesis. It starts by identifying the modules that are affected by the changes in each platform and the appropriate level of detail for the analysis of the different alternatives. The impact of the change is calculated through the Impact Metric and that feeds the estimate of the value of each alternative.

The next phase is the recommendation of the alternatives to pursue. This phase is the result of the analysis where the cost and the value are compared, and a priority for implementation is established. This implementation plan should be reviewed by the firm and the decision would depend on the strategic plan of the company.

The last stage is the implementation of the changes to the platforms in order to respond to the alternatives that were identified and develop new derivative products.

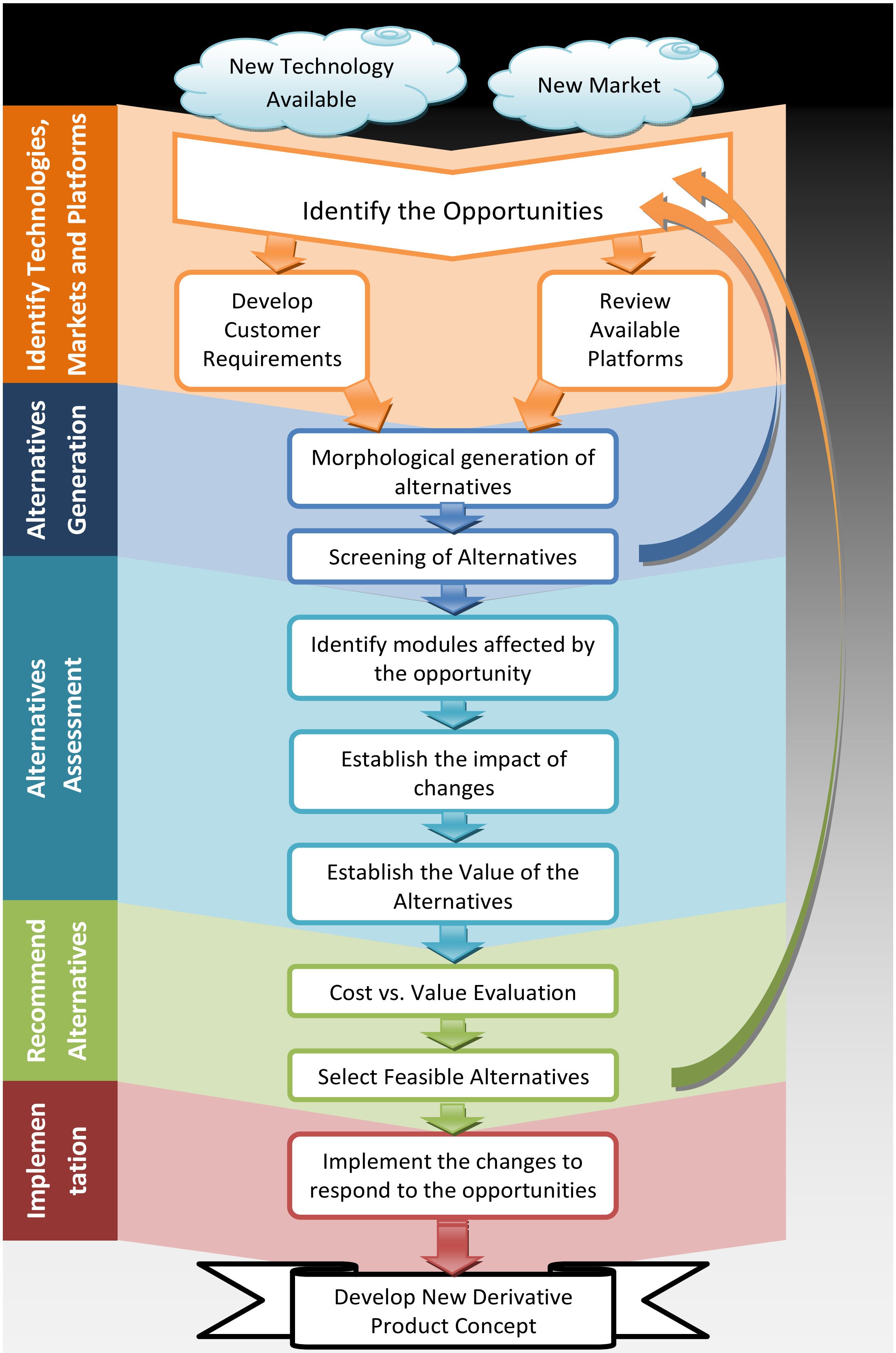


Figure 4 Process Framework Overview

4.2 Alternatives Assessment

After the opportunities have been identified and the platform(s) has (have) been reviewed, the alternatives are generated through a morphological analysis and screened to ruled out the alternatives that are not feasible. The resulting group of alternatives should be evaluated in order to decide which the best alternatives to pursue are.

This assessment is divided into three steps that will be further explained in the following sections: (1) the modules that are affected by the technology integration are identified; (2) an impact assessment estimates how difficult it is to make a change in the elements that were identified; and (3) the value of the alternative is estimated for the company given the different scenarios and possibilities. With this information a recommendation on which are the best alternatives to pursue for the company can be made.

In order to accomplish these three steps, the approach that is summarized in Figure 5 was implemented in this work and will be described below.

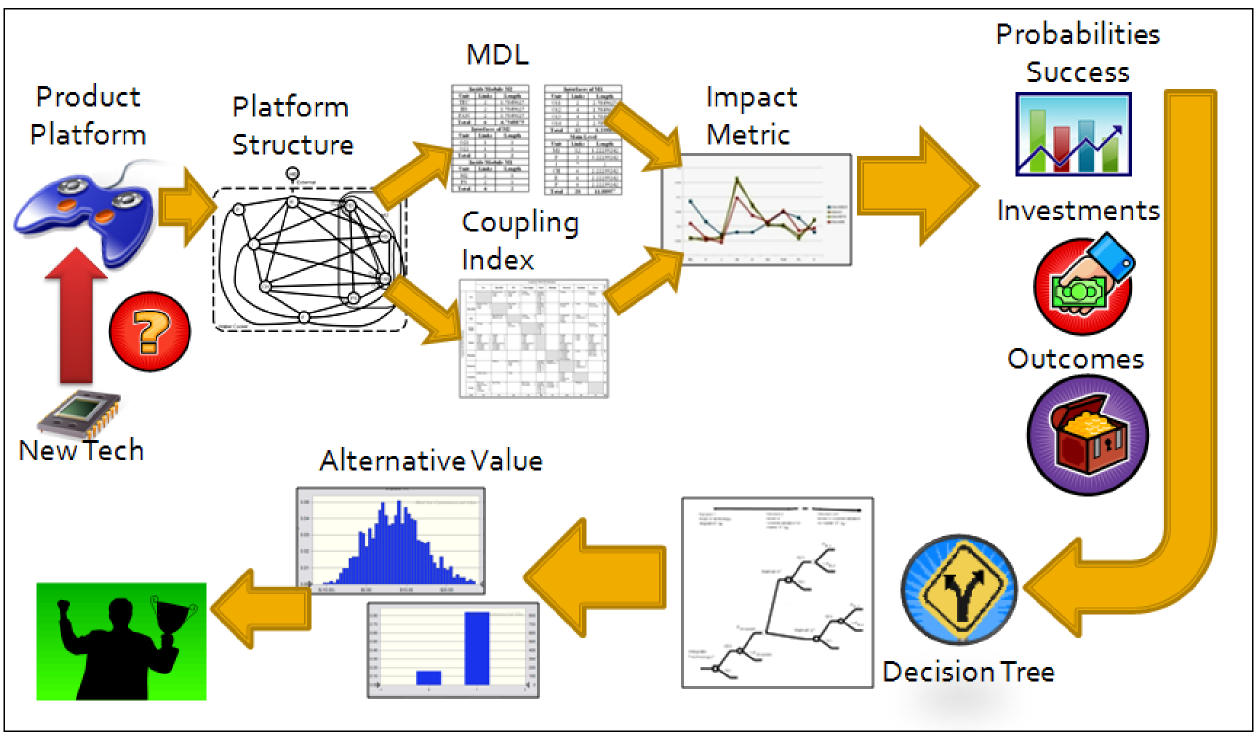


Figure 5 Research Approach Overview

The initial step is that a technology or set of technologies for a given scenario are identified as candidates for insert into an existing platform. The platform is then analyzed and the corresponding impact is calculated by adapting existing tools, which will be described in greater detail in sections 4.2.1 and 4.2.2. Once the impact has been estimated, the assessment continues with the estimation of the value of the new platform to the firm. This is accomplished by relating the impact metric to the valuation process through the parameters that include the required investments, probabilities of success, and possible outcomes for the project. Additional parameters are estimated and populate a decision tree that is the input to a Monte Carlo simulation that calculates the possible range of value outcomes. This valuation process is described in greater detail in section 4.2.3.

The results of these assessments assist the decision maker in the selection of the most appropriate path for the firm to take, which reduces to pursuing the product platform alternatives that yield the greatest likelihood to results in positive financial outcomes for the firm. The details of each step in this process will be examined in the following sections.

4.2.1 Affected Modules Identification

The first step in the assessment is to identify which modules within the platform of the alternative would have to change in order to integrate the technologies identified or to pursue the new markets. This identification implies a review of the platform structure looking at the relationships between components, modules or sub-modules. The review would highlight the indirect elements that are affected and the appropriate level of detail of the analysis would be a natural result of this phase.

4.2.2 Impact Assessment

The next step is to establish what the impact of the changes is for the elements identified in the previous step. This requires that the interactions of the affected elements of the platform are quantified not only by the number of relationships but also in the strength of those relationships, because the premise is that the impact depends on both. In order to do that, the tools explored in section 3.1 are examined.

The commonality indices are not well suited for this evaluation because they do not account for relationships but for number of components as noted in equations 1 and 2. The method of Minimal Description Length developed by Wang [25] gives a general representation of the modularity of the architecture, however in the process it describes each element in terms of the number of relationships and it accounts for the modules defined in the structure, therefore it could be part of the impact measure.

In order to illustrate how Wang's [25] work was adapted in this work, it is useful to consider the simplified example below (adapted from an example in Wang [25]):

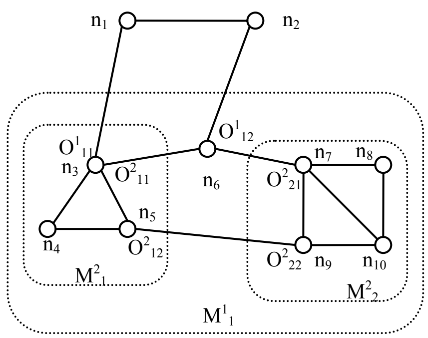


Figure 6 Graph example adapted from [25]

The description of the system would be:

M^1_1 (Module Name) $O^1_{11}O^1_{12}$ (List of Interfaces){

$M^2_1O^2_{11}O^2_{12}${

n_3n_4 (Links)

n_3n_5

n_4n_5}

Level 2 Inside Module M^2_1

$M^2_2O^2_{21}O^2_{22}${

n_7n_8

n_7n_9

n_7n_{10}

n_8n_{10}

n_9n_{10}}

Inside Module M^2_2 (Level; Module #)

$n_6M^2_1O^2_{11}$

$n_6M^2_2O^2_{21}$

$M^2_1O^2_{12}M^2_2O^2_{22}$ (Level; Module #; Interface #)

Level 1 Inside Module M^1_1

n_1n_2

$n_1M^1_1M^2_1O^1_{11}$

$n_2M^1_1O^1_{12}$

Level 0 Product

For the graph shown in Figure 6, the calculation of the MDL representation of the system would be an analysis per level describing each unit in the graph by the number of connections per level. Then the links are measured adding the representation of the units involved. In the end the length of all the links are summed up to get a representation of the system:

*At level 2 (2 layers inside the product)

*Inside M^2_1

Unit	Links	Length
n_3	2	$-\log_2 2/6$ $=\text{Log}_2 3$
n_4	2	$=\text{Log}_2 3$
n_5	2	$=\text{Log}_2 3$
Total	**6**	

Link	Length
n_3n_4	$2\text{Log}_2 3$
n_3n_5	$2\text{Log}_2 3$
n_4n_5	$2\text{Log}_2 3$
Total	**$6\text{Log}_2 3$**

*Inside M^2_2

Unit	Links	Length
n_7	3	$-\log_2 3/10$ $=\text{Log}10/3$
n_8	2	$=\text{Log}_2 5$
n_9	2	$=\text{Log}_2 5$
n_{10}	3	$-\log_2 3/10$ $=\text{Log}10/3$
Total	**10**	

Link	Length
n_7n_8	$\text{Log}_2 10/3 + \text{Log}_2 5$
n_7n_9	$\text{Log}_2 10/3 + \text{Log}_2 5$
n_7n_{10}	$2\text{Log}_2 10/3$
n_8n_{10}	$\text{Log}_2 10/3 + \text{Log}_2 5$
n_9n_{10}	$\text{Log}_2 10/3 + \text{Log}_2 5$
Total	**$6\text{Log}_2 10/3 + 4\text{Log}_2 5$**

*At level 1

*Inside M^1_1

Unit	Links	Length
n_6	2	$-\log_2 2/6$ $=\text{Log}_2 3$
M^2_1	2	$=\text{Log}_2 3$
M^2_2	2	$=\text{Log}_2 3$
Total	**6**	

Interface	Links	Length
O^2_{11}	1	$-\log_2 1/4=2$
O^2_{12}	1	$=2$
O^2_{21}	1	$=2$
O^2_{22}	1	$=2$
Total	**4**	

Link	Length
$n_6M^2_1O^2_{11}$	$2\text{Log}_2 3 + 2$
$n_6M^2_2O^2_{21}$	$2\text{Log}_2 3 + 2$
$M^2_1O^2_{12}M^2_2O^2_{22}$	$2\text{Log}_2 3 + 4$
Total	**$6\text{Log}_2 3 + 8$**

*At level 0

Unit	Links	Length
n_1	2	$-\log_2 2/6$ $=\text{Log}_2 3$
n_2	2	$=\text{Log}_2 3$
M^1_1	2	$=\text{Log}_2 3$
Total	**6**	

Interfaces	Links	Length
O^1_{11}	1	$-\log_2 1/2$ $=1$
O^1_{12}	1	$-\log_2 1/2$ $=1$
Total	**2**	

Link	Length
n_1n_2	$2\text{Log}_2 3$
$n_1 M^1_1M^2_1O^1_{11}$	$3\text{Log}_2 3 + 1$
$n_2M^1_1O^1_{12}$	$2\text{Log}_2 3 + 1$
Total	**$7\text{Log}_2 3 + 2$**

*Total

L_d = Length of links at level 0 + length of links at level 1 + length of links at level 2

$L_d = (7\text{Log}_2 3 + 2) + (6\text{Log}_2 3 + 8) + [(6\text{Log}_2 10/3 + 4\text{Log}_2 5) + (6\text{Log}_2 3)]$

$L_d = 19\text{Log}_2 3 + 6\text{Log}_2 10/3 + 4\text{Log}_2 5 + 10 = 59.8238$ bits

This number is a representation of the entire system. However the methodology would serve to characterize just a module or a component giving a representation of each one in terms of the number of connections related to that unit in each level. Returning to the example described above, the unit n_1 has two relationships with the rest of the system, one with unit n_2 and another with module M^1_1, and a total of 6 relationships at level 0, then the representation of n_1 would be $-\log_2(2/6) = 1.585$. For units that have relationships outside modules, like unit n_3, the representation should account for that so it would be not just its description inside Module M^2_1 but the sum of the interfaces that it represents (O^1_{11} and O^2_{11}) so it would be $-\log_2(2/6) -\log_2(1/2) -\log_2(1/4) = \log_2(3)+3 = 4.585$.

As discussed in the literature review, this quantification does not take into account that the strength of the links are different between each other and a relationship between two units may be stronger (therefore hard to modify) than other.

Another tool may be helpful in quantifying the strength of relationships is the DSM. The DSM analyzes the relationships but out of the multiple approaches in the use of the DSM probably the ones that capture the differences in the strength of the relationships are the Coupling Indices. Introduced by Martin and Ishii [36, 37], the CI analyzes the strength of each connection creating a matrix that relate the components and how they supply and require information. Each cell evaluates the sensitivity of the component to a change based on the scale described in Table 1.

The CI represents how strongly related each component is with the rest of the system. It also differentiates if the components supply or require information to/from other components. Because it is a representation on a component basis it is compatibles with the MDL representation in the sense that it would highlight different aspects of the relationships in a structure, which is necessary for a more complete assessment of the impact of changing an element in a platform.

Other tools explored in the literature review are not suited for this evaluation, the Non-Zero Fraction and the SMI give a global idea of the modularity of a product and it cannot be broken down by components. The modularity index developed by Guo and Gershenson [35] is also a general indication of how modular a product is, however it can be broken down by the

contribution of its components as long as they are in the same level, when there are module boundaries it is difficult to recognize the contribution of each component inside the modules to the general modularity of the product.

These characterizations can be normalized by dividing the length of each component with the total length of the system in order to compare the results when they are applied in the same system. Applying this to a Water Cooler (further studied in section 5) it was clear that there are differences in the description that one can obtain with the MDL method and the CI, a comparison can be seen in Figure 7.

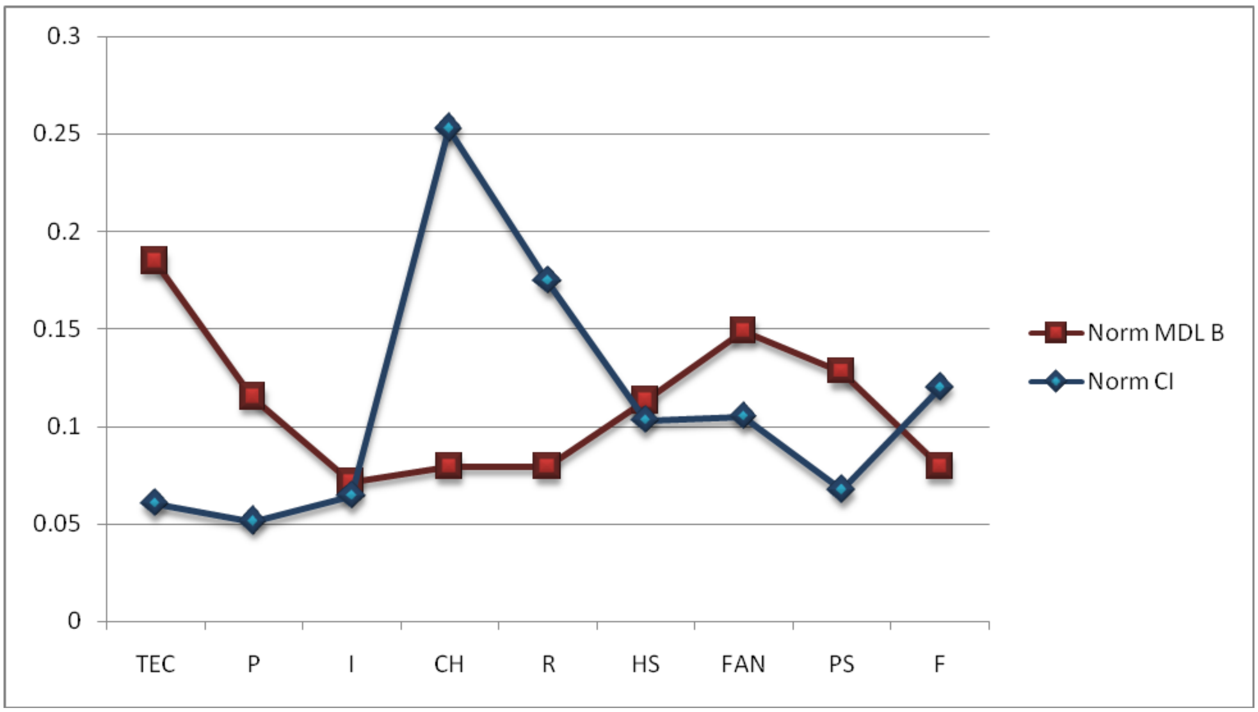


Figure 7 CI and MDL comparison on a water cooler.

This comparison suggests that combining the concept of CI with the MDL could give a better representation of the impact of making a change to the platform, thus forming the basis for a new impact metric.

A first attempt was to multiply the length of each link by the sensitivity of the component (extracted from the CI matrix) and then add all the links related with each component; however this metric seemed to be dominated entirely by the sensitivity as can be seen in Figure 8. The problem with this approach seems to be the difference in the units (MDL in bits and the CI in a

big number as a result of a summation of 3, 6, and 9s in the sensitivity analysis) that when combined in each link made it meaningless.

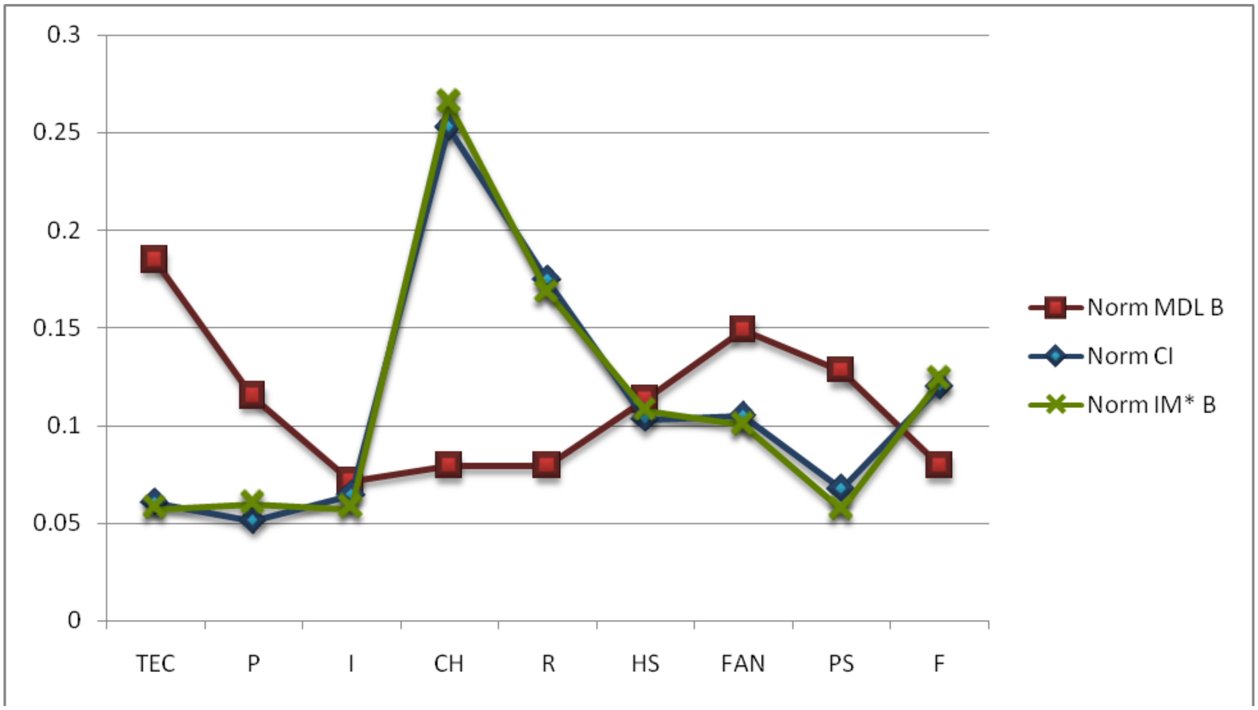


Figure 8 First attempt on the development of the impact metric.

After several iterations a more successful approach that reflects both dimensions of complexity (number and strength of connections) was:

$$IM_u = (CI-R_u + CI-S_u) \times \sum_{i=0}^{n} (L_u^i + O_u^i) \qquad (13)$$

where:

IM_u is the impact of a change in unit u,

u is the unit (module or component) that is under analysis,

$CI\text{-}R_u$ is the Coupling Index Receiving for unit u,

$CI\text{-}S_u$ is the Coupling Index Supplying for unit u,

n is the number of modules that contain unit u,

i is the level of the architecture that is under analysis,

L_u^i is the MDL of the unit u and level i, and

O_u^i is the MDL of the interfaces that represent unit u at level i.

This attempt was once again tried on the Water Cooler to verify the assumption and as can be seen in Figure 9 the new impact metric developed highlights the most important findings of both original metrics.

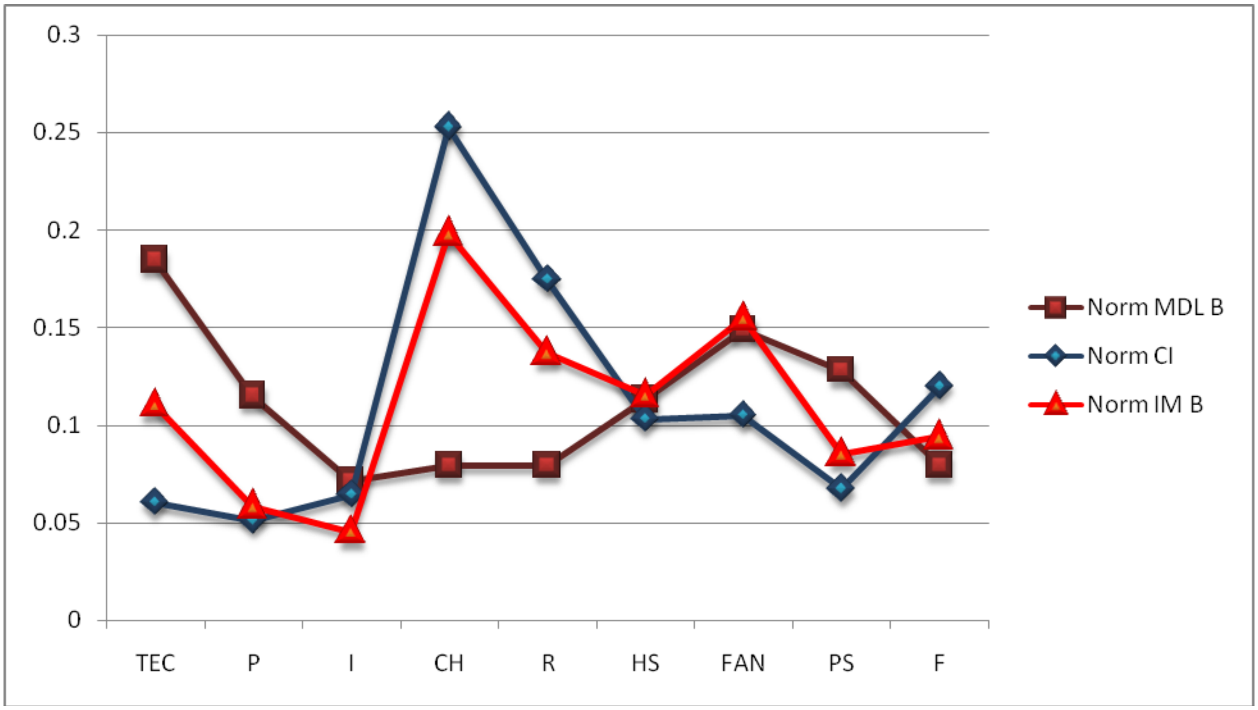


Figure 9 Successful attempt on the development of the impact metric.

As stated previously, this attempt seems to capture the elements highlighted by the individual metrics which was the goal of the Impact Metric being a representation of the difficulty to implement a change in an element of the platform based on the number of relationships and their strength that needs to be considered.

Looking closely at Figure 9 it is clear that the element TEC was among the less relevant components of the platform according to the CI, while it was the most significant in the MDL approach. The new IM reconciles both tools and highlights this element as the fourth most relevant. Another interesting case is the element CH which was by far the most coupled element in the platform but not relevant under the MDL approach; IM preserves this element as the most significant of the platform but diminish the difference with the rest of the components.

It is necessary to recognize that the Impact Metric developed is a good approach based on the observations that have been conducted but it does not mean that this is the most appropriate way

to combine CI and MDL. The formulation may require a tuning process, the inclusion of scaling factors, and the difference in the units used in the CI (arbitrary) and the MDL (bits) may need to be considered, but in the meantime it serves the purpose to describe the impact of change in each one of the elements of a product.

Having this representation defined, the next step is the estimation of the value of a given scenario to facilitate the decision on what the best alternative for the firm is.

4.2.3 Value Assessment

In order to assess the value of a given alternative we need to consider a complete scenario of technologies to integrate and markets to pursue. Faulkner [47] as well as Gonzalez-Zugasti et al. [51] used decision trees as a way to model different alternatives for platform-based product family development, however these decision trees were meant to analyze the whole development process of a platform (see Figure 3); in our case, the development starts with platforms already defined, therefore the decision tree needs to be adapted and generalized for these types of cases (see Figure 10).

This model is applied after several (Q) markets have been identified and a platform has been selected as the most promising to integrate the technology or technologies in order to develop a derivate that could cover the needs of at least one of the markets. The formulation of the scenario and the selection of each of the variables are left for future work.

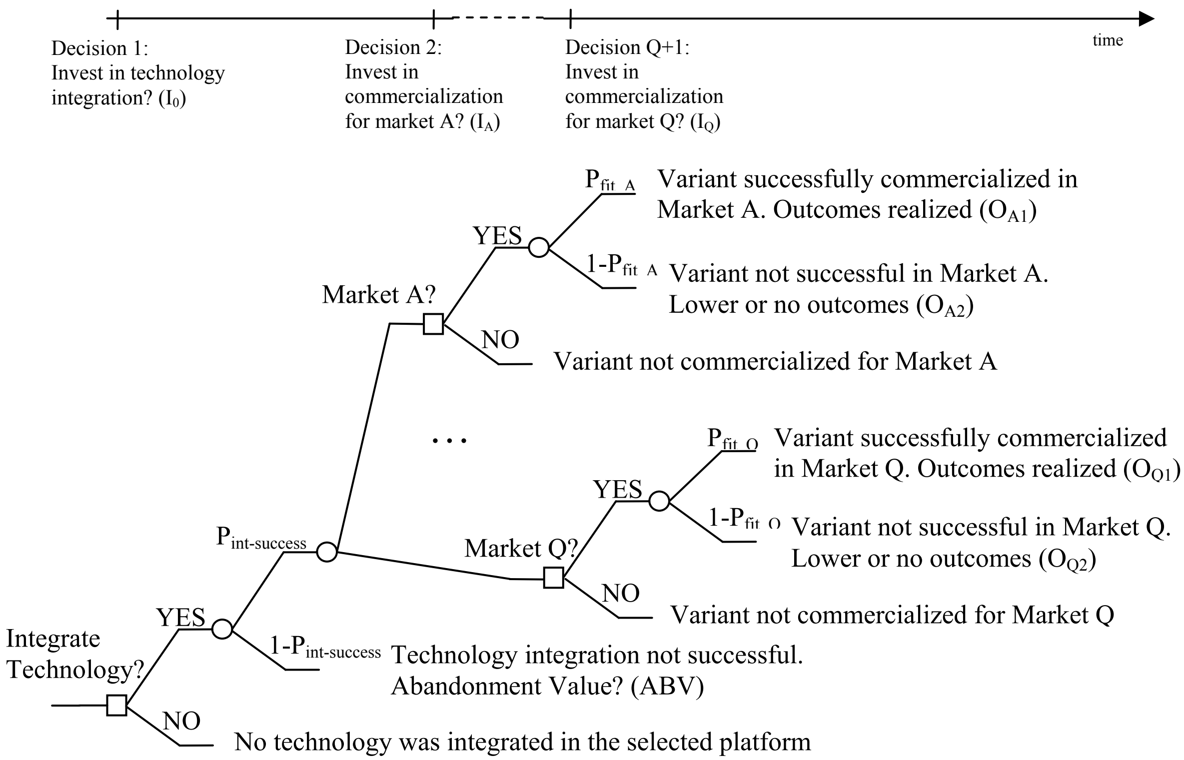


Figure 10 Decision Tree for technology integration

According to this model, the value of a given alternative would depend on the possible outcomes of the commercialization of the product in the different markets (O), the probability of successful integration ($P_{int\text{-}success}$), the probability of fit of the product in the different markets (P_{fit}) and the required investments (I). An abandonment value could be considered as a way to account for benefits that could be obtained in the process of technology integration that would not depend on the successful development of variants of a given platform. The abandonment value could include, for example, the value of equipment that need to be purchased for the integration of technology but can be sold at the moment to cancel the project. That gives the opportunity to link the impact assessment with the value estimation having *IM* as a proxy for cost and *im* as a proxy for the probability of successful integration. The value is calculated as follows:

$$V_{k-h} = P_{\text{int}-success} \cdot \left[\max\left\{ \frac{\left(P_{fit\,A}.O_{A1} + \left(1 - P_{fit\,A}\right).O_{A2}\right)}{\left(1+ir\right)^{tc_A}} - \frac{I_A}{\left(1+ir\right)^{ti_A}}, 0 \right\} + \ldots \right.$$

$$\left. + \max\left\{ \frac{\left(P_{fit\,Q}.O_{Q1} + \left(1 - P_{fit\,Q}\right).O_{Q2}\right)}{\left(1+ir\right)^{tc_Q}} - \frac{I_Q}{\left(1+ir\right)^{ti_Q}}, 0 \right\} \right] + \left(1 - P_{\text{int}-success}\right). \frac{ABV}{\left(1+ir\right)^{ta}} - I_0 \quad (14)$$

$$V_{k-h} = P_{\text{int}-success} \cdot \left[\sum_{j=1}^{Q} \left(\max\left\{ \frac{\left(P_{fit\,j}.O_{j1} + \left(1 - P_{fit\,j}\right).O_{j2}\right)}{\left(1+ir\right)^{tc_j}} - \frac{I_j}{\left(1+ir\right)^{ti_j}}, 0 \right\} \right) \right] + \left(1 - P_{\text{int}-success}\right). \frac{ABV}{\left(1+ir\right)^{ta}} - I_0$$

where:

$V_{k\text{-}h}$ is the value of integrating technology *k* in platform *h*,

$P_{int\text{-}success}$ is the probability of a successful integration of technology *k* in platform *h*,

$P_{fit\,A}$ is the probability of success of the variant in market *A*,

O_{A1} is the expected outcome or payoff of the successful product in market *A*,

O_{A2} is the expected outcome or payoff of the non-successful product in market *A*,

I_A is the investment required to commercialize the product in market *A*,

Q is the number of identified markets of possible fits with technology *k* and platform *h*,

$P_{fit\,Q}$ is the probability of success of the variant in market *Q*,

O_{Q1} is the expected outcome or payoff of the successful product in market *Q*,

O_{Q2} is the expected outcome or payoff of the non-successful product in market *Q*,

I_Q is the investment required to commercialize the product in market *Q*,

ABV is the abandonment value of the technology integration,

I_0 is the investment required to develop the technology integration and generate a variant.

The operator max represents the ability to exercise the option to commercialize the variant in a given market only if it seems to surpass the investment required to do it, otherwise the value is 0 that represents the decision of not to commercialize the variant in that market.

In order to better understand the value estimation model, a detailed explanation of each of the parameters involved can be found in the following paragraphs.

The probability of successful technology integration ($P_{int\text{-}success}$) depends on how difficult the integration is, and how much the platform has to change in order to incorporate the new technology, therefore it could be expressed in terms of the impact metric (IM) developed in the

previous section. The normalized impact metric (*im*) was used because it was already bounded between 0 and 1, therefore the probability of success in the technology integration is inverse to the effort that is required to change the platform.

$$P_{\text{int}-success} = 1 - \sum_{i=1}^{n} im_i \times \alpha_i \qquad (15)$$

where:

im_i is the normalized impact metric of each component/module at the level of the analysis,

n is the number of components/modules defined at the level of analysis,

α_i =1 if the component/module changes with the technology integration or,

α_i =0 if the component/module does not change with the technology integration.

The investment required to develop the technology integration (I_0) would depend not only on how difficult it is to integrate the technology but also on the nature of the industry that is developing the product. A scaling factor beta has been used to capture the relationship between investment and IM. This scaling factor could be determined by looking at historical data of how much it cost to integrate a new technology and what its IM was. The premise is that this scaling factor is industry dependant but it requires further research to verify this relationship. Therefore the investment could be estimated as follows:

$$I_0 = \left(\sum_{i=1}^{n} IM_i \times \alpha_i \right) \times \beta \qquad (16)$$

where:

IM_i is the impact metric of each component/module at the level of the analysis,

n is the number of components/modules defined at the level of analysis,

α_i =1 if the component/module changes with the technology integration or,

α_i =0 if the component/module does not change with the technology integration,

β is the scaling factor according to the nature of the industry that is developing the product relating the investment in dollars with the IM of the elements [$/IM#].

The estimation of *beta* has been considered for the application case of the following chapter as the slope of the trend in investments and IM for different technology integration projects of the company (see Figure 16).

The probability of success of the variant in a given market (P_{fit}) would be given by a Monte Carlo simulation with the characteristics of the market and the characteristics of the product that would be introduced. In order to mitigate the errors in the estimation a probability distribution could be fit for this parameter. Gonzalez-Zugasti et al. [51] suggested that this probability could be linked to the customer requirements and the performance of the variant in order to fulfill those requirements, estimating probability distributions for both (requirements and performance) and analyzing if those intersect for each of the selected parameters. For this work, it was assumed that the company would be able to determine the probability distributions for this parameter based on the market studies conducted for the project.

The investment required to commercialize the product in a given market (I_A) would depend on the market that is being pursued and the type of product. However the investment could be estimated based on historical data and a probability distribution can capture the possible deviations from that estimate. For this work, it was assumed that the historical data was available for the company and that similar projects have been realized, allowing the firm to estimate the values for this parameter.

To conclude, the expected outcome or payoff of the product in a given market should be estimated in two scenarios, the successful and the non-successful introduction of the product in the market. The first could be the goal of market share for the variant under development while the second could be a pessimistic scenario of the introduction of the variant in the market; the marketing department of the firm would have a great input at this stage because through their market studies the forecast could be more accurate. The outcome can be modeled as a probability distribution to account for the variability in the response.

4.2.3.1 Value Simulation

The decision tree is then run through a Monte Carlo simulation where the stochastic values are sampled several times from the probability distributions used to model those parameters giving an idea of the possible outcomes of the development, characterizing in this way the opportunities that the company has to pursue.

The decision on whether to implement the changes on the platform integrating the uncovered technologies would depend on the interests and strategies of the corporation. However the information extracted with the simulation would facilitate the assessment to the decision makers and would give quantifiable means to support the selection taken.

5 Application Case

The alternative assessment section of the framework was applied to a thermoelectric water cooler platform initially studied by Mark Martin in his doctoral thesis [36] and subsequent journal article [37]. An exploded view of the system can be seen in Figure 11.

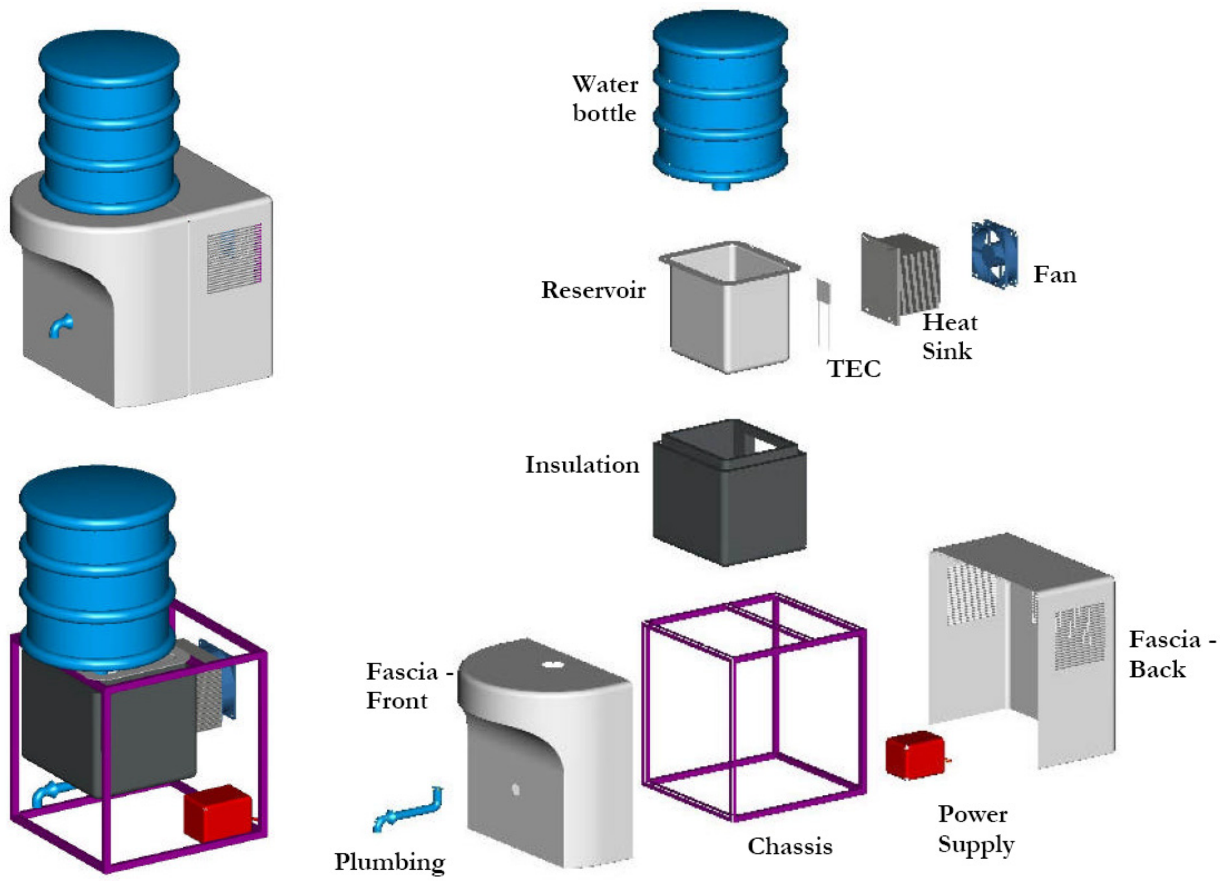


Figure 11 Water cooler [36]

For the purpose of the case study, the following scenario was proposed: A company that produces water coolers is considering a new technology of Thermo-Electric Coolers (TEC) that has become available with substantial improvements in efficiency. The company currently has two platforms in the market (A and B) where the technology could be useful to pursue a new market of ultra efficient water coolers. In which platform should the technology be integrated? A? B? Both? None?

Platform A has no modules defined at the level that is under analysis (see Figure 12), on the other hand Platform B has two modules grouping the electric components: the TEC, the heat sink, the fan, and the power supply (see Figure 13) in order to facilitate the outsourcing of those components.

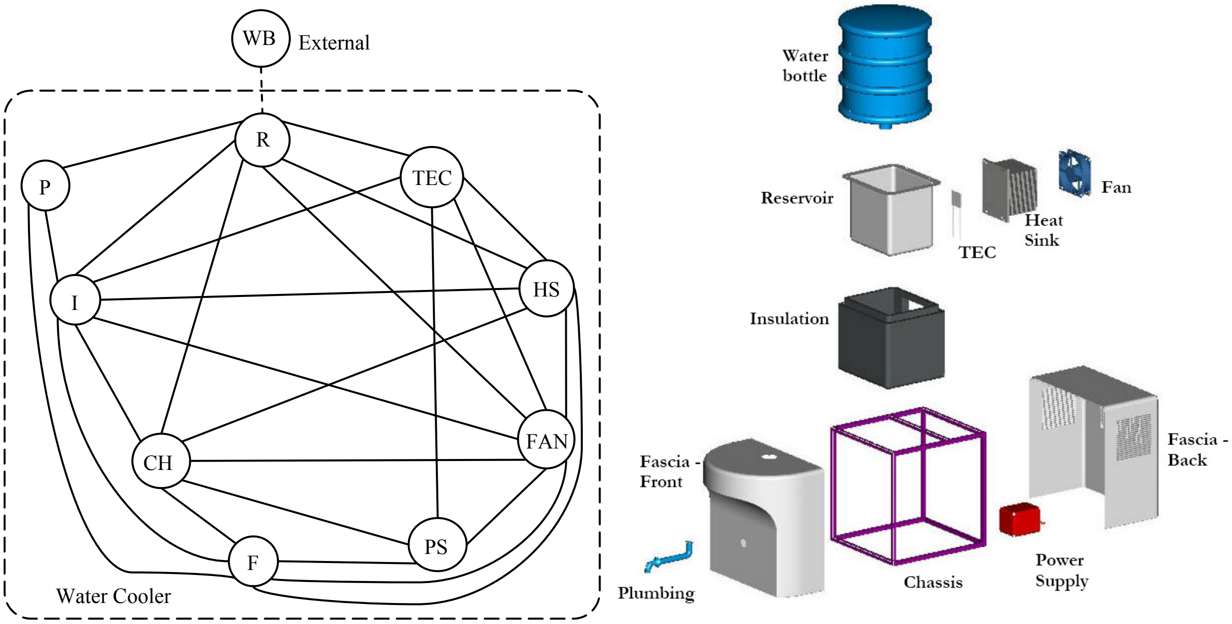


Figure 12 Water cooler's Platform A

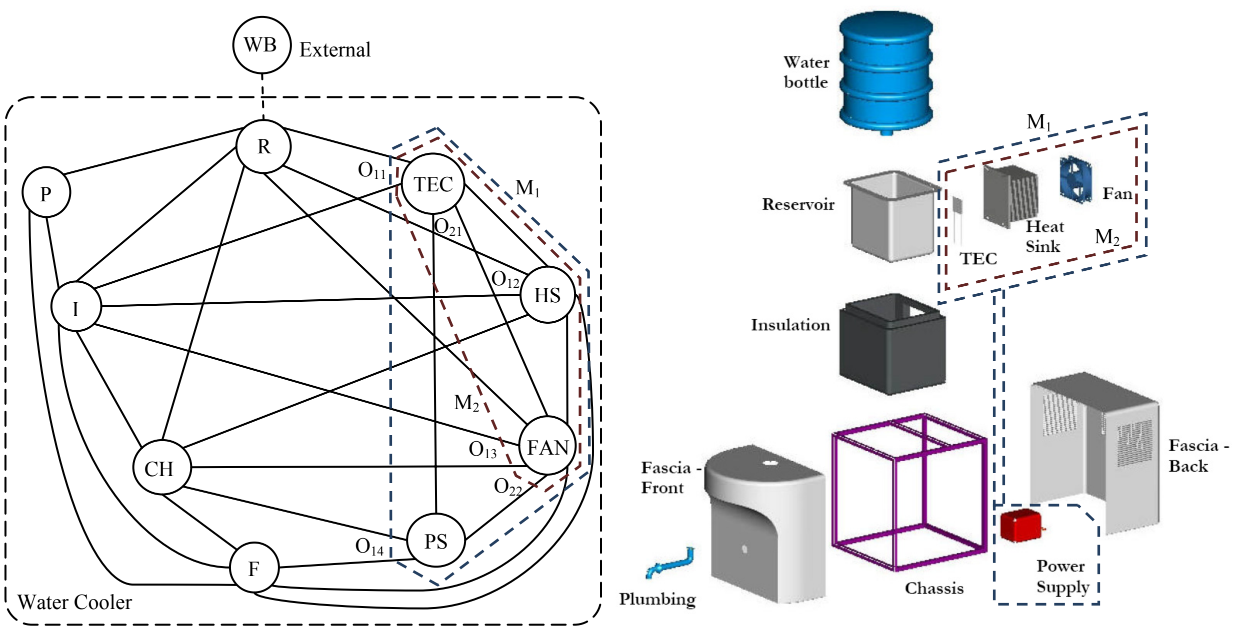


Figure 13 Water cooler's Platform B

The following assumptions were made in order to complete the scenario:

- The integration of the technology would affect not only the TEC but the design of the Reservoir (R), the Heat Sink (HS), and the Fan.
- The goal for market share out of this variant has been estimated at $120 million.
- The commercialization of the water cooler is estimated at $15 million but it could go from $10 to $23 million based on historical data.
- There is historical data of similar technology integration projects.
- The probability of market success is estimated at 0.4 but it could go from 0.2 to 0.7.
- The abandonment value is considered around $10 million.

After the technology to integrate has been identified, along with the elements that would be affected, and the platforms have been reviewed with an understanding of the structure of the available platforms, the assessment of the alternatives can proceed to the impact assessment.

5.1 Impact Assessment

The next step is to characterize each element of the platforms (see Figure 12 and Figure 13, WB is Water Bottle, R is Reservoir, I is Insulation, CH is Chassis, P is Plumbing, HS is the Heat Sink, PS is Power Supply, and F is Fascia) and evaluate the graphs according to the MDL.

First the MDL calculations are made for the Platform A of the water cooler (without modules defined), the results are shown in Table 3. The lengths are normalized dividing each one by the sum of all lengths.

Table 3. MDL estimation for water cooler Platform A.

Unit	Links	Length		Norm MDL1
TEC	5	$-Log_2 5/50$ $=Log_2 10$	3.321928095	0.114813493
P	3	$Log_2 50/3$	4.058893689	0.140284723
I	7	$Log_2 50/7$	2.836501268	0.098036023
CH	6	$Log_2 25/3$	3.058893689	0.105722417
R	6	$Log_2 25/3$	3.058893689	0.105722417
HS	6	$Log_2 25/3$	3.058893689	0.105722417
FAN	7	$Log_2 50/7$	2.836501268	0.098036023
PS	4	$Log_2 25/2$	3.64385619	0.12594007
F	6	$Log_2 25/3$	3.058893689	0.105722417
Total	**50**	**28.93325527**		**1**

The graph of the platform B is also analyzed and the results of the MDL calculations can be seen in Table 4.

Table 4. MDL estimation for water cooler Platform B.

Inside Module M2			
Unit	**Links**	**Length**	
TEC	2	1.5849625	
HS	2	1.5849625	
FAN	2	1.5849625	
Total	**6**	**4.7548875**	
Interfaces of M2			
Unit	**Links**	**Length**	
O21	1	1	
O22	1	1	
Total	**2**	**2**	
Inside Module M1			
Unit	**Links**	**Length**	
M2	2	1	
PS	2	1	
Total	**4**	**2**	
Interfaces of M1			
Unit	**Links**	**Length**	
O11	2	2.5849625	
O12	4	1.5849625	
O13	4	1.5849625	
O14	2	2.5849625	
Total	**12**	**8.33985**	
Main Level			
Unit	**Links**	**Length**	
M1	12	1.22239242	
P	3	3.22239242	
I	7	2	
CH	6	2.22239242	
R	6	2.22239242	
F	6	2.22239242	
Total	**28**	**11.88957**	
General			
Unit	**Length**		**Norm MDL2**
TEC	$=TEC+O_{11}+O_{21}$	5.169925001	0.18474372
P		3.222392421	0.11514998
I		2	0.071468627
CH		2.222392421	0.079415667
R		2.222392421	0.079415667
HS	$=HS+O_{12}$	3.169925001	0.113275093
FAN	$=FAN+O_{13}+O_{22}$	4.169925001	0.149009406
PS	$=PS+O_{14}$	3.584962501	0.128106173
F		2.222392421	0.079415667
Total	**27.98430719**		**1**

The MDL description changes significantly going from Platform A to Platform B, and that is precisely what it should reflect, the complexity of the architecture. A comparative graph can be seen in Figure 14.

The CI matrix developed by Martin [36] already contains the CI-R and CI-S for the water cooler (see Table 5) and that does not vary in either platform according to the assumptions.

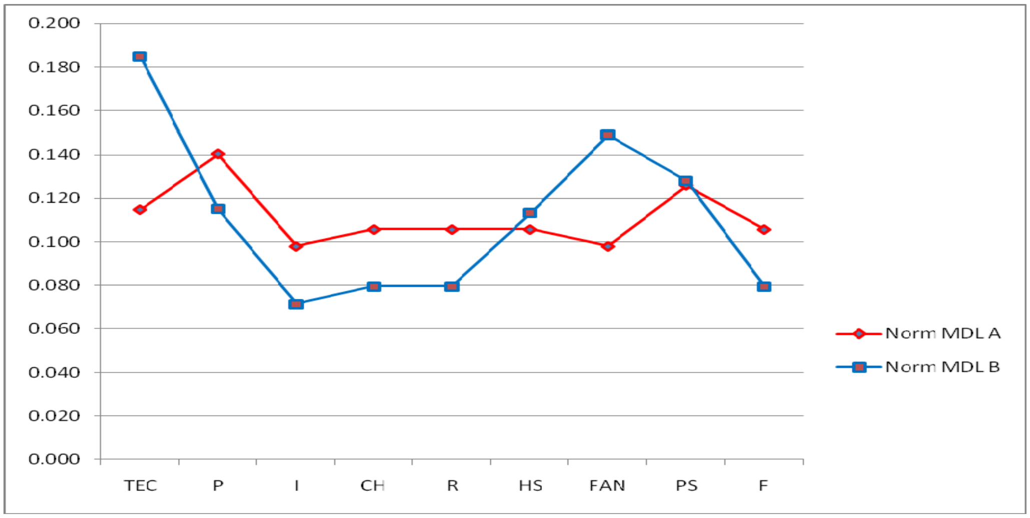


Figure 14 MDL comparison for water cooler's Platform A and B

Table 5. CI Matrix for the water cooler [36]

	Components SUPPLYING Information									
Components REQUIRING Information	**Fan**	**Heat Sink**	**TEC**	**Power Supply**	**Chassis**	**Plumbing**	**Reservoir**	**Insulation**	**Fascia**	**CI-R**
Fan		Pressure resist 9 X dim 3 Z dim 3	Heat output 3 X dim 1 Z dim 1	Voltage 9 P-P voltage 1	Strength 1 Mounting Points 3 X dim 1 Y dim 9 Z dim 1		Volume 3		Vent area 3 Thickness 1	**52**
Heat Sink	Pressure Curve 3 X dim 3 Z dim 3		Heat output 3 X dim 3 Z dim 3		Strength 1 Mounting Points 3 X dim 6 Y dim 6 Z dim 1		Absorptivity 1 Volume 6	Y dim 3	Vent area 3 Vent location 3	**51**
TEC		Heat Sink cond 3 Effective area 3		Voltage 9 P-P voltage 3			Conductivity 3 X dim 1 Z dim 1 Volume 6	Y dim 3 Conductivity 3		**35**
Power Supply	Voltage 9		Imax 3 Resistance 3		Strength 1 Mounting Points 1 X dim 1 Y dim 1 Z dim 1				Vent area 1 Vent location 3	**24**
Chassis	Weight 1 X dim 1 Y dim 3 Z dim 1 Mounting Holes 9 X location 1 Y location 3 Z location 1	Weight 3 X dim 1 Y dim 9 Z dim 1 Mounting Holes 9 X location 3 Y location 3 Z location 1		Weight 3 X dim 1 Y dim 1 Z dim 1 Mounting Holes 9 X location 1 Y location 1 Z location 1			Weight 3 X dim 9 Y dim 9 Z dim 3 Mounting Holes 9 X location 9 Y location 9 Z location 3	X dim 1 Y dim 3 Z dim 1	Weight 1 X dim 3 Y dim 3 Z dim 3 Mounting Holes 9 X location 3 Y location 3 Z location 3	**155**
Plumbing							Water height 1 X location 3 Y location 3 Z location 3 Hole diameter 3	Z dim 3	Hole X loc 3 Hole Z loc 3 Hole radius 3	**25**
Reservoir		Radiance 1	Heat plumbing 3 X dim 1 Z dim 1		Strength 3 Mounting Points 9 X dim 6 Y dim 6 Z dim 3	Diameter 3 Fitting Type 9		X dim 3 Y dim 3 Z dim 3 Conductivity 3		**57**
Insulation	Airflow direct 3		Y dim 1				X dim 9 Y dim 9 Z dim 9 Conductivity 1 Volume 3			**38**
Fascia	Flow rate 3 Airflow direct 3 X dim 1 Y dim 3 Y location 3	Max Temp 1		Max Temp 1 Heat output 3	Strength 3 Mounting Points 9 X dim 9 Y dim 6 Z dim 9	Diameter 3 X location 6 Z location 6		Thickness 1		**70**
CI-S	**54**	**53**	**26**	**44**	**100**	**27**	**119**	**30**	**41**	**504**

Having the MDL description for both platforms and the CI the IM is calculated according to equation 13 for both architectures. The results are observed in Table 6 with CI = CI-R + CI-S.

Table 6. IM estimation for water cooler.

Unit	CI	MDL - A	IM – A	MDL - B	IM - B
TEC	61	3.3219	202.6376138	5.1699	315.3654251
P	52	4.0589	211.0624718	3.2224	167.5644059
I	65	2.8365	184.3725824	2	130
CH	255	3.0589	780.0178907	2.2224	566.7100674
R	176	3.0589	538.3652893	2.2224	391.1410662
HS	104	3.0589	318.1249437	3.1699	329.6722002
FAN	106	2.8365	300.6691344	4.1699	442.0120502
PS	68	3.6439	247.7822209	3.5850	243.77745
F	121	3.0589	370.1261364	2.2224	268.909483
Total	**1008**	**28.9332**	**3153.158283**	**27.9843**	**2855.152148**

These calculations for IM can be normalized in the same way as the MDL in order to plot the different metrics on the same scale to perform the analysis (see Figure 15).

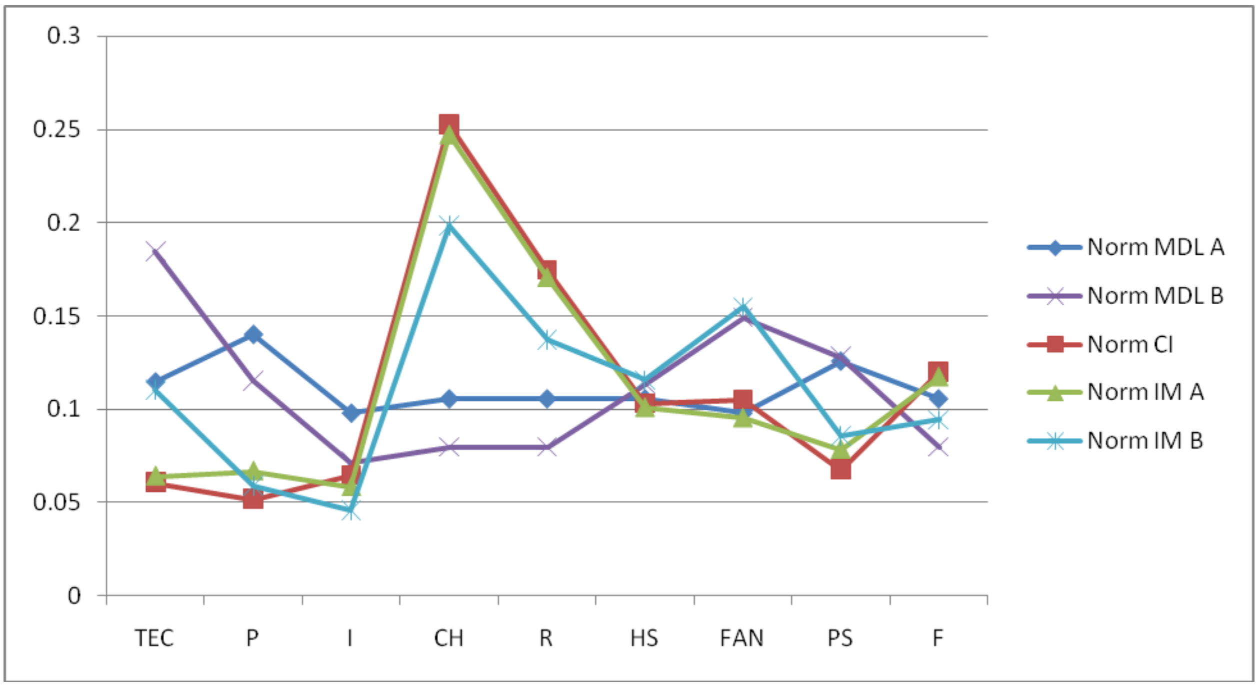


Figure 15 Metric comparison for water cooler

Looking at the graph it is easy to see that in the first architecture the impact is dominated by the coupling and the element that would be more difficult to change is the chassis (CH); however, in the second case the MDL description of the architecture highlights other components like the Fan which is now inside two modules and therefore its changes would be more difficult, but preserve the chassis as the component that would have the biggest impact on the system. This example shows how the new metric extracts the most important findings of both tools and

provide a more complete analysis of the system that facilitate the assessment of a change in a certain platform or product.

5.2 Value Assessment

With the IM calculated for both platforms (platform A with no modules defined and platform B with two modules defined), a decision tree was formed for each platform in order to estimate the value of integrating the technology into the platform.

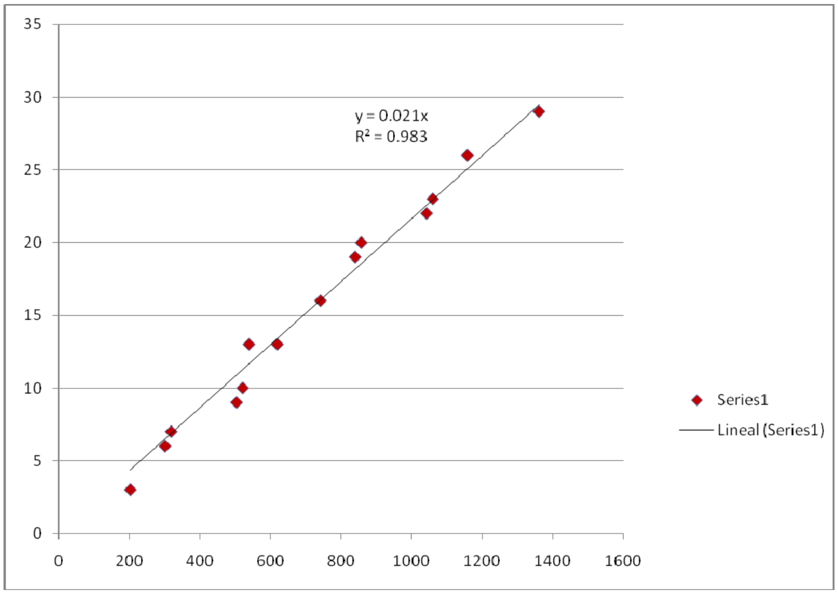
First, the parameters involved in the decision tree need to be established; those were the initial investment, the probability of integration success, the abandonment value, the commercialization investment, the probability of market success, and the outcome for success and failure.

The initial investment depends on the Impact Metric (IM), which is different for each platform, and the scaling factor *beta* that corresponds to the industry involved in the change. The factor *alpha* was used to select the components that were affected by the technology integration. For platform A it was estimated as indicated in equation 16 and can be seen in Table 7.

Table 7. I_0 estimation for water cooler change with platform A.

Component	IM – A	alpha	Beta
TEC	202.637614	1	0.02
Plumbing	211.062472	0	
Insulation	184.372582	0	
Chassis	780.017891	0	
Reservoir	538.365289	1	
Heat Sink	318.124944	1	
Fan	300.669134	1	
Power Supply	247.782221	0	
Fascia	370.126136	0	
$\mathbf{I_{0A}}$	**27.1959396**		

For the estimation of *beta*, historical data was assumed and a relationship between IM and Investment was established from which the slope of the trend line was set as the scaling factor. In Figure 16 can be seen the values assumed for past integration projects that involved one or several elements of interest of the case study.



Unit	Cost ($M)	IM A
TEC	3	202.637614
R	13	538.365289
HS	7	318.124944
Fan	6	300.669134
T.R	16	741.002903
T.HS	10	520.762557
T.Fan	9	503.306748
R.HS	20	856.490233
R.Fan	19	839.034424
HS.Fan	13	618.794078
T.R.HS	23	1059.12785
T.R.Fan	22	1041.67204
R.HS.Fan	26	1157.15937
T.R.HS.Fan	29	1359.79698
Beta		**0.02169263**

Figure 16 *Beta* estimation for Water Cooler

Then the probability of integration success was estimated as a function of the normalized impact metric (im) of the components that would be affected by the technology integration (see Table 8). The factor *alpha* was used again to select the elements affected by the technology integration.

Table 8. $P_{int-success}$ estimation for Water cooler change with platform A.

Component	im – A	alpha
TEC	0.06426497	1
Plumbing	0.06693685	0
Insulation	0.05847235	0
Chassis	0.2473767	0
Reservoir	0.17073843	1
Heat Sink	0.10089089	1
Fan	0.09535491	1
Power Supply	0.07858223	0
Fascia	0.11738267	0
$P_{int-success}$	**0.5687508**	

The commercialization investment and the probability of market success were modeled as triangular distributions while the outcomes for success and failure were modeled as normal distributions. The shape of the distributions was not the main focus of this research therefore they were modeled with the best judgment possible but it is clear that further studies should be conducted in order to determine the appropriate shapes. A summary of the distributions used for those parameters can be seen in Table 9:

Table 9. Distributions attributes for simulation parameters.

Attribute	I_A	$P_{fit\ A}$
Minimum	10	0.2
Likeliest	15	0.4
Maximum	23	0.7
Attribute	O_{A1}	O_{A2}
Mean	120	50
Standard Deviation	20	15

Having all of the parameters for the simulation (see the summary in Table 10), the decision tree was modeled using Microsoft Excel and Crystal Ball (see Figure 17) and a Monte Carlo simulation was conducted in order to establish the possible outcomes of the scenario.

Table 10. Simulation parameters for Water cooler change with platform A.

Initial Investment	I_0	27.20
Prob. Integration Success	$P_{int\text{-}success}$	0.569
Abandonment Value	ABV	10
Commerc. Investment	I_A	15
Prob. Market Success	$P_{fit\ A}$	0.4
Outcome Success	O_{A1}	120
Outcome Failure	O_{A2}	50
Interest rate	ir	8%

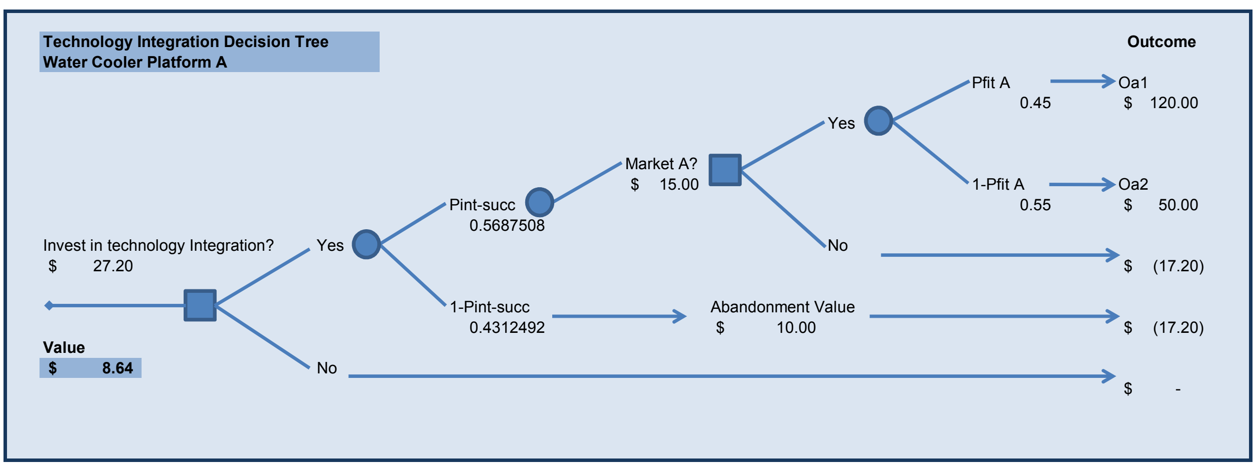


Figure 17 Decision Tree for technology integration in Water Cooler platform A

The results of the simulation can be seen in Figure 18 and Figure 19 where the value of the alternative was calculated and the ratio between the cases where the project was profitable for the company was monitored.

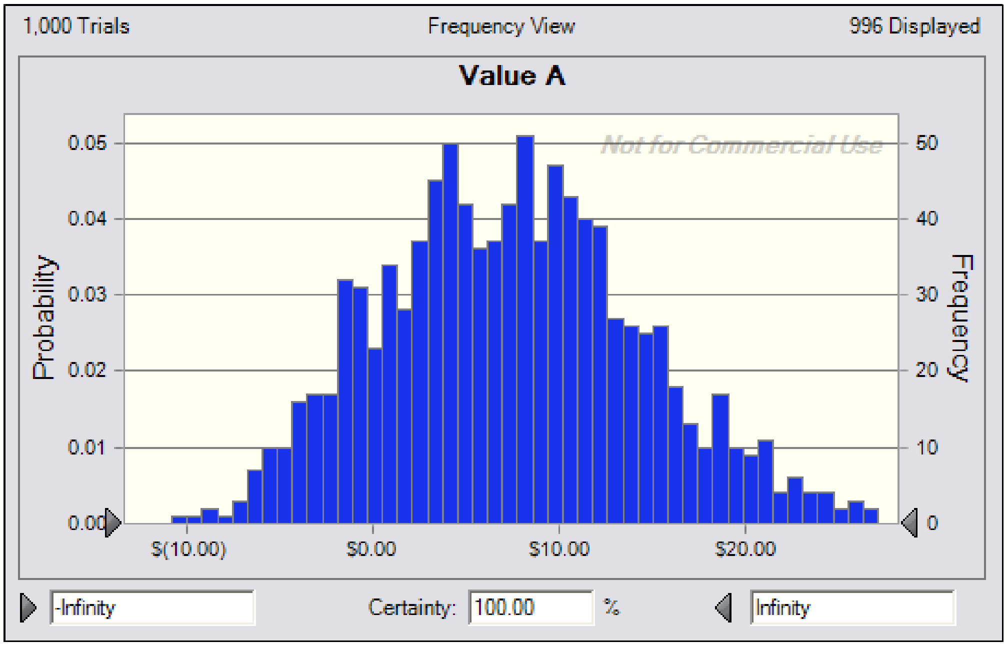


Figure 18 Simulation Result for Value of Alternative with platform A

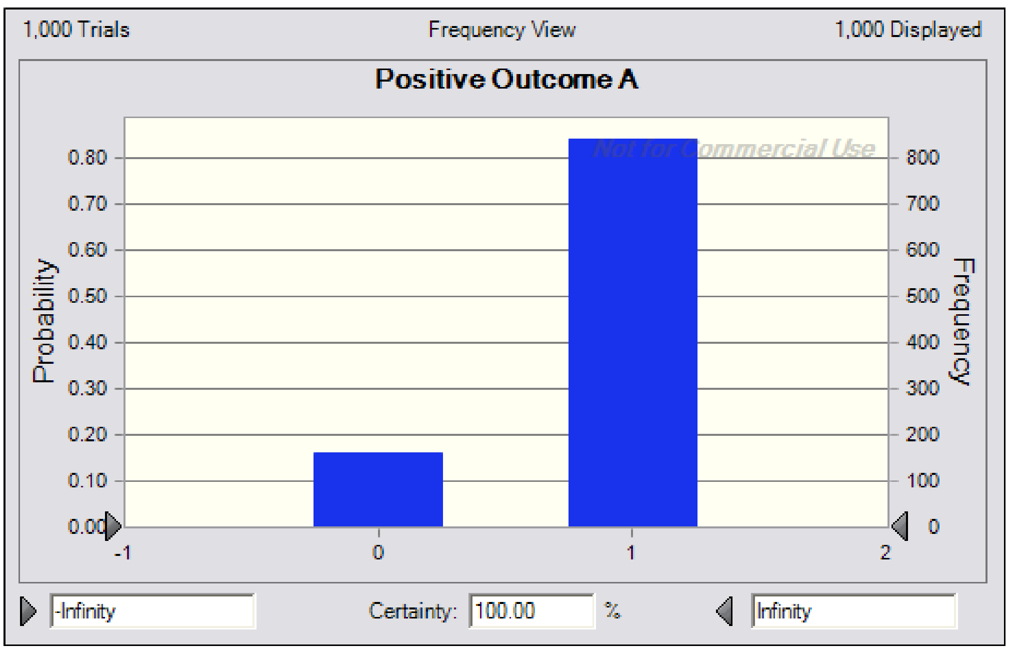


Figure 19 Simulation result for cases of positive outcome with platform A

According to the results of the simulation, it is clear that there is a great chance for obtaining good outcomes of the project of integrating the technology in platform A in order to generate a derivative product. The mean of the results for the value is $7.38 million and the standard deviation is $7.07 million which could be a very attractive scenario for the company.

For platform B the same simulation was conducted but first the initial investment and the probability of successful integration were recalculated with the corresponding IM for that platform (see Table 11 and Table 12). Once all the parameters were updated the decision tree for platform B (see Figure 20) was set and the simulation was conducted.

Table 11. I_0 estimation for Water cooler change with platform B.

Component	IM – B	alpha	beta
TEC	315.365425	1	0.02
P	167.564406	0	
I	130	0	
CH	566.710067	0	
R	391.141066	1	
HS	329.6722	1	
FAN	442.01205	1	
PS	243.77745	0	
F	268.909483	0	
I_0	**29.5638148**		

Table 12. $P_{int\text{-}success}$ estimation for Water cooler change with platform B.

Component	im – B	Alpha
TEC	0.06426497	1
P	0.06693685	0
I	0.05847235	0
CH	0.2473767	0
R	0.17073843	1
HS	0.10089089	1
FAN	0.09535491	1
PS	0.07858223	0
F	0.11738267	0
$P_{int\text{-}success}$	**0.48227251**	

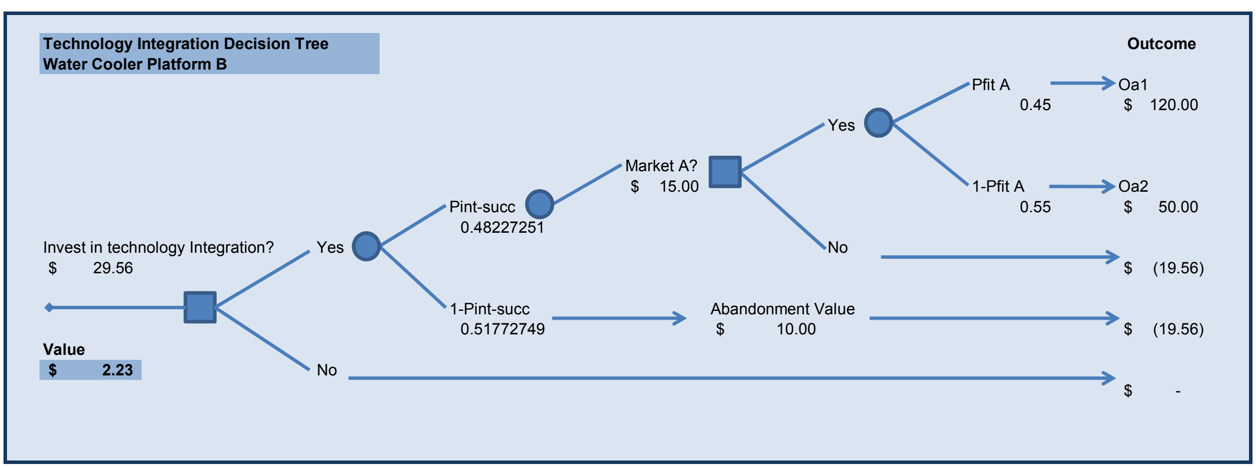


Figure 20 Decision Tree for technology integration in Water Cooler platform B

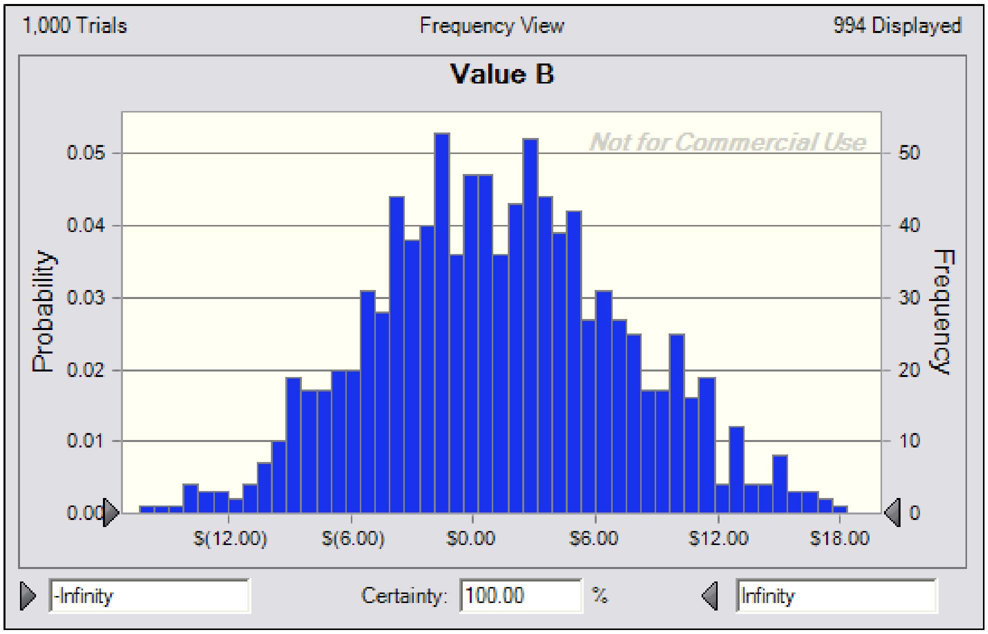


Figure 21 Simulation Result for Value of Alternative with platform B

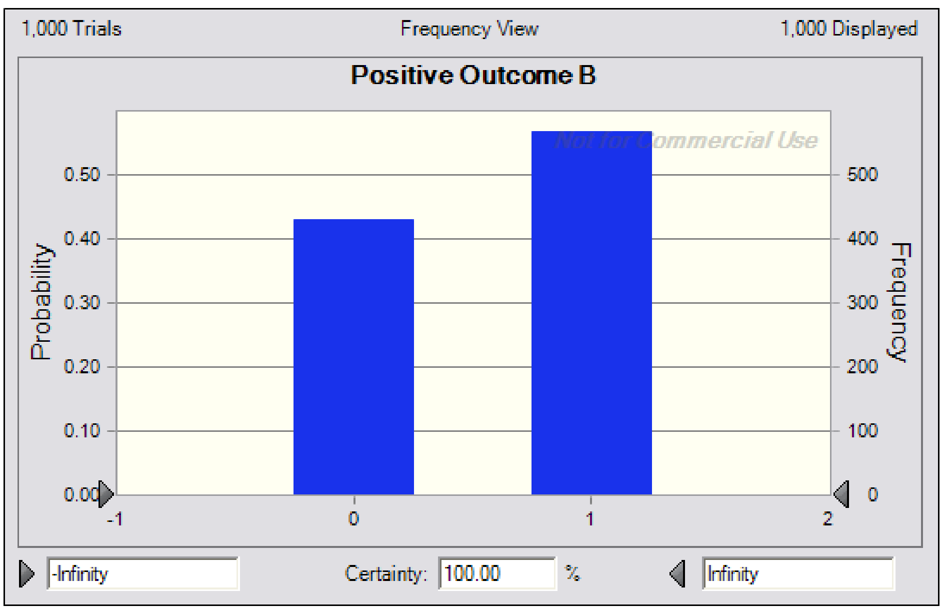


Figure 22 Simulation result for positive outcome with platform B

The results of the simulation for platform B of the Water Cooler (see Figure 21 and Figure 22) show that the project would be much riskier having almost 50% of the cases of the simulation where the technology integration did not produce a positive outcome. The mean of the value was $1.36 million and the standard deviation was $6.32 million.

6 Discussion

Looking at the results of the simulation of the case study, Platform A would be more appropriate for the technology integration given the assumptions of the scenario. Platform B would be a much riskier project but nevertheless, if the conditions are favorable could represent a significant benefit for the firm, therefore it would depend on the company, its corporate strategy, the available resources, among other factors, to take the decision of whether or not to integrate the new technology into the platform.

This conclusion makes sense because the platform that contains more boundaries (Platform B) would have more concerns associated with it due to interactions across boundaries. These concerns include the preservation of the sub-modules, modules, and the system in order to maintain the integrity of the product if no other change in the relationships is considered.

The drawing of an artificial boundary to define the modules in the water cooler overlooked relevant aspects of a real case, since module definition would probably imply the inclusion of new elements in the platform to facilitate the interface between the module and the rest of the system (such as connectors), and the minimization of the interactions outside the modules.

The IM seemed to capture differences in platform architectures at a component level and served as a means to estimate the difficulty of changing a certain element. However the formulation of the IM may require a tuning process or a different way to combine the CI and the MDL that accounts for the dissimilarity in the units of these base tools.

The method proposed to calculate the scaling factor for the required investment (*beta*) seems reasonable for a company that keeps detail information regarding the costs of projects. However it would have to be applied in real companies to verify the feasibility of this procedure and the assumption of the relationship between this factor and the nature of the industry.

The selection of the probability distributions may have been arbitrary for the case study in this work and perhaps not the most appropriate, however the purpose of the case was to illustrate the process and further study is necessary to obtain a better representation of each one of the parameters and the distributions to use in the valuation model.

Nevertheless the application of the proposed model would provide insights into the possible outcomes of the project that would allow the decision maker to pursue the integration of technologies into established platforms with more confidence. That type of aid with decisions that involve large amounts of money with uncertain outcomes could be very valuable. It would facilitate the exploration of alternatives that may be not only profitable for the firm, but may also provide the opportunity to retain and grow market share that otherwise would be reduced or lost.

7 Conclusions and Future Work

A new metric was developed to estimate the impact of a change in a platform based on existing tools that analyzed the relationships in an architecture both in number and strength. Even though the approach developed has shown interesting and useful results with the case study, it is acknowledged that the formulation will require adjustments and improvements that could be made through the application of the model to other cases, including real product development projects. This type of application would also allow the verification of the assumptions made in the process.

Given that is was noted previously that most impact metrics do not incorporate the strength of the interaction in their formulation, the use of the impact metric developed in this work on new platform development is also possible

A decision tree model was adapted to estimate the value of the alternatives providing valuable insights in the possible outcomes of the project. The Monte Carlo simulation used in the model proved to be an important technique to explore different scenarios and account for uncertainty in many stages of the technology integration in established platforms.

An important contribution of this work was that the value estimation was linked to impact of change through the options model which facilitates the assessment process of the alternatives that are considered for the technology integration scenario.

Two conference papers were published from this work [10, 56] which yielded valuable feedback from researchers in the field. It was noted that the approach used was unique and provided different insights in an area that has been under constant research.

For future work it is important to validate the assumptions of the relationship between impact of changes and cost of the technology integration project in order to keep moving forward with the application of the selection framework. This was one of the main assumptions made in the value estimation phase and it seems a natural correlation, however there is no real data that backs up this premise, therefore it needs to be further explored.

It is also important to verify that the scaling factor *beta* is industry dependant or company dependant to be able to fully characterize the alternatives in the estimation of the required investment for the technology integration process. Such verification could be accomplished by studying historical data on investments for technology integration projects in one or several firms, then correlating these with the resulting impact metric calculations for the corresponding platforms. Which technologies and which components impacted would be irrelevant because the relationship of interest is the relationship of the cost per unit of impact metric change. It is possible that this may be a universal relationship, an industry-specific relationship, a company-specific relationship, etc.

The application of the decision framework to a real application case becomes crucial to clarify the parameters in the model and verify the assumptions made at every step of the way. Having access to real data would allow the refinement of the tools and methods proposed making more valuable the framework for real adoption of the methods.

Another field that should be further explored is the relationship between the probability of fit of the variant in the selected market and the specifications developed at the early stages of the product development process. In this way the alternative assessment of a project for technology integration would be more meaningful and would provide the firm with even more precise information on the possible outcomes of the project facilitating the decision process of whether or not to undertake such endeavors.

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