

A ROBUST DESIGN APPLICABILITY MODEL

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Abstract

This paper introduces a model for assessing the applicability of Robust Design (RD) in a project or organisation. The intention of the Robust Design Applicability Model (RDAM) is to provide support for decisions by engineering management considering the relevant level of RD activities. The applicability assessment is based on two considerations: 1) Whether there is a correlation between the factors that are important to the project or organisation and the factors that impact from the use of RD and 2) What is the occurrence level of the given factor in the organisation. The RDAM defines RD to be applicable in organisations assigning a high importance to one or more factors that are known to be impacted by RD, while also experiencing a high level of occurrence of this factor. The RDAM supplements existing maturity models and metrics to provide a comprehensive set of data to support management decisions. The factors in the RDAM were derived by analysing a combination of RD literature and industrial cases involving RD. The RDAM is used on a case company to illustrate its use.

Keywords: Robust design, Design management, Organisation of product development, Design for X, (DfX)

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1 INTRODUCTION

The purpose of this paper is to present a Robust Design Applicability Model (RDAM) for measuring the applicability of Robust Design (RD) as a means of improving the intended performance criteria of a project and/or an organisation.

In order to achieve and maintain profitability and competitiveness, production companies are constantly striving to improve their processes. Within the field of product development and production, a wide array of frameworks and methods such as LEAN, Design for Six Sigma, Design for Manufacture, Reliability Engineering, Robust Design Methods etc. are available for supporting process improvements and for optimising performance parameters such as scrap rates, lead time, functional variation etc. Although all of the available frameworks and methods potentially create value for the organisation, there are significant costs of implementation and use. Limitations on resources and considerations as to how many changes the organisation is capable of handling simultaneously constitute a practical limit on the number of methods an organisation can implement at one time, as well as the level of depth each method is taken to. Hence, the management is faced with the decision on which frameworks and methods are most relevant in terms of improving the overall performance of the organisation and to which level they should be taken.

This paper seeks to identify and define ways of supporting this decision and is therefore targeted at managers and practitioners within engineering design and quality engineering, working with design processes and methods.

It is not the aim of the paper to make a comparison of various frameworks, but rather to present a model for assessing the specific framework of Robust Design, as experience and surveys have shown that the industrial uptake of RD is limited. This is done by answering the research question:

How can an organisation identify the applicability of Robust Design?

The paper opens with a Theoretical Background providing an overview of the existing state-of-the-art, followed by a Methodology-section, describing how the RDM was developed. Then, the resulting RDM is described along with an example of how it has been applied on a case organisation. Finally, the implications and further research potential of the RDM are discussed and the conclusion sums up the main findings.

2 THEORETICAL BACKGROUND

The process of developing a new product comprises a number of phases, each containing certain activities (Pahl & Beitz 1984, Ulrich & Eppinger 2011). Depending on the size and type of the organisation, the process and activities can be more or less formally defined in a process model, e.g. a stage-gate model. The organisation then has an interest in optimising the types, levels and competencies of these activities. RD is an example of a set of tools and methods that aim to improve the reliability of a product's performance by reducing the sensitivity of the product's functions to variations in its design parameters. Robustness is seen as a subset of reliability: A reliable product is defined as a product with the ability to "perform its intended function during a specified period of time under stated conditions" (Elsayed 2012) and for a given variation of a product's design parameters, a robust product will perform more consistently and will therefore also be more reliable. The RD framework contains a wide array of practices (Hasenkamp 2009) and tools (Eifler et al 2013) and can potentially be applied at various levels in terms of which practices and tools are used as well as the resources allocated to apply them.

For organisations of a certain size there will be several activities running in parallel and resources are allocated to each activity based on the expected benefit to the organisation. As a part of defining the optimal level of activities within a given field, maturity measurements can be used. Measurement of project or organisational maturity on the topics of reliability and robustness are of interest both to improve business performance and to develop the products' robustness characteristics. The term "mature" is defined by Andersen et al (2003) to be "in perfect condition to achieve its objectives" which represents an unrealisable target for many organisations. When measuring maturity the question is therefore not "whether or not" the organisation's practices are mature, but rather "what is the level of maturity". Several guidelines for developing maturity models are provided and recommendations are summarised in Pfleger (1995), Maier et al (2012), Mettler (2011), and Tiku (2007). Maturity

models should typically (i) Be tied to the needs of the organisation, (ii) Start small and grow according to needs and resources, and (iii) Support visualizing aspects of interest (of the process). On a general level this mapping and corresponding measurements are necessary parts of process improvements. Various maturity models are already available for measuring and benchmarking the organisation's maturity or capability within several fields; for example, Maier et al (2012) identifies 61 maturity models ranging from "R&D Effectiveness" to "Effective Teamwork". These maturity models are often based on an assessment of various entities on a predefined scale (Khoshgoftar et al 2009), with a clearly specified set of requirements necessary to reach the next maturity level. The nature of a maturity model can vary depending on the aim and scenario. They can be: 1) Descriptive, giving an 'as-is' picture of the current maturity level, 2) Prescriptive, defining the target levels of the organisation or 3) Comparative, comparing the maturity level with e.g. competitors, sites within the same organisation or an identified best-practice organisation. Assuming that advancing to a higher level requires organisational change, training and additional activities, advancing towards and maintaining a high maturity level requires resources. Therefore, reaching the highest possible level of maturity within all aspects may not be the optimal solution for the organisation. The management must consider the costs and benefits associated with each level of maturity and define the relevant target levels. Within the field of reliability and robustness, the Institute for Electrical and Electronics Engineers (IEEE) has developed a standard (IEEE1624 2008) that outlines eight different practices, including aspects such as planning, training, analysis and testing, supply chain management, failure analysis, verification and improvements. The maturity of each practice can be assessed on a defined Likert scale with five levels.

Information about the current maturity level could be supplemented by information about the relevance of the field in question, as shown in Figure 1. Performance metrics, such as production yield, customer complaint rates, process capabilities, launch date precision etc. give some indication on current performance. Perera (2006) gives an example of how reliability metrics can be used on product level and Ebro et al (2014) and Ebro et al (2012) list a series of relevant metrics for defining the robustness of a product. These metrics can be based on specific products or product lines, but can also comprise the entire product portfolio to show a more complete picture of the overall performance of the organisation. However, the metrics are descriptive - they do not contain inherent targets and do not provide information about their importance for the overall success of the organisation and in some cases, the relevant metrics may not be available or used at all. Finally, the metrics are not weighted or prioritised, i.e. they do not include information about the level of impact they have on the organisation, compared to other metrics. Essentially maturity models measure the level of activities and methods in an organisation, but do not provide information on the actual performance nor the relevance of carrying out the activities, meaning that there is a blind spot for the decision makers.



Figure 1. Maturity Models measure the activities, methods and skills of an organisation, but typically do not measure the aspect of applicability of the given field.

Ideally, decisions on whether to apply RD, and the level of resources to allocate to this set of activities, would be based on specific knowledge about both the maturity and the applicability of Robust Design. For example, it is not sufficient to know that the customer complaint rate is 0.6% and that the organisation is at 'level 3' in all aspects related to robustness - to complete the picture, it is relevant to also know how important in-use failures are to the organisation, as this can vary greatly depending on the product and market expectations. Because the aspect of Maturity is already covered by e.g. IEEE1624, the paper will focus mainly on the concept of Applicability.

3 RESEARCH METHODOLOGY

To identify how the use of RD impacts a company, a case analysis was applied, as this was considered to give a more authentic picture than theoretical descriptions of effects. Cases, which have had the direct involvement of one or more of the authors, either in the role as consultant, engineer or researcher were selected. The cases come from companies in four different European countries

(Norway, Sweden, Great Britain, and Denmark) and cover a wide range of businesses including defence, medical devices, aerospace and consumer electronics. The criteria for selecting the cases were the authors' involvement and knowledge of them. It should be noted that the identified set of impact factors therefore do not necessarily constitute a definitive, but rather a comprehensive set. The case descriptions are based on a combination of company statements, project reports, project descriptions, steering committee conclusions and ongoing discussions between the authors and the case companies.

The methodology builds on the assumption that if an organisation assign impact factors associated with RD high importance then RD is likely to be applicable in the organisation. The assessment of the applicability is further strengthened by also including an assessment of the occurrence-level of the given impact factor, as this indicates the current level of performance. As an example, if an organisation defines the factor *launch date precision* as highly important, and this factor is recognised to be impacted by RD methods, and the percentage of launch date delays is high, then it is likely RD is applicable in that organisation.

The insights from the industrial companies are structured based on common characteristics of their initial undesired situations and the main impact factors they wanted to influence. An impact model is used to capture and visualise the case data, see Figure 2. In general terms an impact model describes the relationships between certain input factors and their corresponding outcomes. Impact models have different purposes and can be used to guide and support research or to establish a statistical relationship between variables and the corresponding validation of this relationship. Within research on engineering design, the impact model presented in Design Research Methodology (DRM) by Blessing and Chakrabarti (2009) describes "the desired situation and shows the assumed impact of the support to be developed". Underlying the term "model" is an assumption that a "certain something" is likely to exist in reality. Models are simplified representations of reality, they are not theories, but they can be used to represent a theory. The DRM authors acknowledge that an impact model can be built up based on input from literature, but also various other sources such as "assumptions, experience, research goals, focus, questions and hypotheses" (p.20). This paper makes use of a combination of literature and experience from industrial cases to derive the presented Impact Model.

It is assumed that each of the factors in the Impact Model represent factors that are impacted by Robust Design and therefore an organisation that finds any of these factors to be important, could benefit from using RD. Therefore, each impact factor in the Impact Model is transferred to the RDAM, where they appear as assessment points that are rated by the organisation in terms of their importance. To illustrate the use of the RDAM, an assessment of a potential client for a RD consulting project was assessed to clarify whether the issues they faced (high impact + high occurrence) were likely to be impacted by using RD.

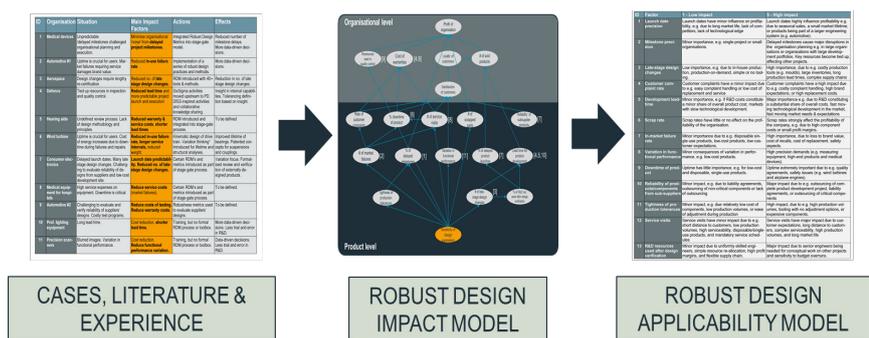


Figure 2. The Applicability Model is derived by analysing robust design-cases from industry and literature to identify the factors impacted by RD. These factors are visualised in an Impact Model and used as assessment points in the Applicability Model.

4 THE ROBUST DESIGN APPLICABILITY MODEL

This section describes the RDAM along with the intermediate results from the analysis of case studies and the Impact Model.

4.1 Impact Model

The Robust Design Impact Model is a generic model that ideally covers all factors related to the robustness of products. Although it is generic, individual organisations will assign different levels of importance to the different impact factors, and some factors may not be relevant at all to a given organisation. The impact model was developed using an analysis of industry cases known to the authors and combined with knowledge from literature on RD metrics and effects. The industrial cases were gathered from the authors' experience from different research projects and work as consultants in various European organisations. The criterion for the selection of cases was that the organisation has decided to work with RD and has initiated certain RD activities. The description of the cases can be seen in Table 1. Four of the cases are also described in more detail by Krogstie et al (2014). The cases represent various fields and come from four different European countries.

Table 1. Organisations that have worked with Robust Design. The table lists 1) their initial situation, 2) the main impact factors that they had identified as being important and that drove the Robust Design initiative, 3) the content of their Robust Design initiative and 4) the experienced effects. The highlighted impact factors were transferred to the Impact Model

ID	Organisation	Situation	Main Impact Factors	Actions	Effects
1	Medical devices	Unpredictable /delayed milestones challenged organisational planning and execution.	Minimise organisational 'noise' from delayed project milestones.	Integrated Robust Design Metrics into stage-gate model.	Reduced number of milestone delays. More data-driven decisions.
2	Automotive #1	Uptime is crucial for users. Market failures requiring service damages brand value.	Reduced in-use failure rate.	Implementation of a series of robust design practices and methods.	More data-driven decisions.
3	Aerospace	Design changes require lengthy re-certification.	Reduced no. of late stage design changes.	RDM introduced with 40+ tools & methods.	Reduction in no. of late stage design changes.
4	Defence	Tied up resources in inspection and quality control.	Reduced lead time and more predictable project launch and execution	SixSigma activities moved upstream to PD. DfSS-inspired activities and collaborative knowledge sharing.	Insight in internal capabilities. Tolerancing definition based on insight.
5	Hearing aids	Undefined review process. Lack of design methodology and principles.	Reduced warranty & service costs, shorter lead times	RDM introduced and integrated into stage-gate process.	To be defined
6	Wind turbine	Uptime is crucial for users. Cost of energy increases due to downtime during failures and repairs.	Reduced in-use failure rate, longer service intervals, reduced weight.	Kinematic design of drive train. Variation thinking ¹ introduced for lifetime and structural analyses.	Improved lifetime of bearings. Patented concepts for suspensions and couplings.
7	Consumer electronics	Delayed launch dates. Many late stage design changes. Challenging to evaluate reliability of designs from suppliers and low-cost development site.	Launch date predictability. Reduced no. of late-stage design changes.	Certain RDM's and metrics introduced as part of stage-gate process.	Variation focus. Formalised review and verification of externally designed products.
8	Medical equipment for hospitals	High service expenses on equipment. Downtime is critical.	Reduce service costs (market failures).	Certain RDM's and metrics introduced as part of stage-gate process.	To be defined.
9	Automotive #2	Challenging to evaluate and verify reliability of suppliers' designs. Costly test programs.	Reduce costs of testing. Reduce warranty costs.	Robustness metrics used to evaluate suppliers' designs.	To be defined.
10	Prof. lighting equipment	Long lead time.	Cost reduction, shorter lead time.	Training, but no formal RDM process or toolbox.	More data-driven decisions. Less trial and error in R&D.
11	Precision scanners	Blurred images. Variation in functional performance.	Cost reduction. Reduce functional performance variation.	Training, but no formal RDM process or toolbox.	Data-driven decisions. Less trial and error in R&D.

¹ Variation Thinking is a term used to describe that e.g. structural analyses, are not only based on nominal values, but also take into account the five different types of variation (Ebro et al 2012) that can change the geometry.

An impact model can contain multiple levels. As an example, the sensitivity of a design can impact the tightness of tolerances, which again can impact the ramp-up time and the scrap rate. The position of the factors in the Impact Model reflects the abstraction level of each factor. At the bottom of the model, the starting point is the "sensitivity of design parameters", which is essentially the main objective of RD. The sensitivity impacts on factors at a higher level, such as the number of market failures. This again impacts on factors at an even higher level, and ultimately, the profit of the organisation is impacted. Obviously, the profit of the organisation is a function of many other factors, but only the ones related to RD are shown in the figure. The identified impact factors from the cases were analysed and structured in a RD Impact Model as shown in Figure 3. Based on a combination of literature knowledge and experience, the impact model was extended with known impact factors not seen in the chosen cases. Furthermore, chains of impact factors were derived, i.e. each of the identified impact factors were analysed to identify the related impact factors in either direction.

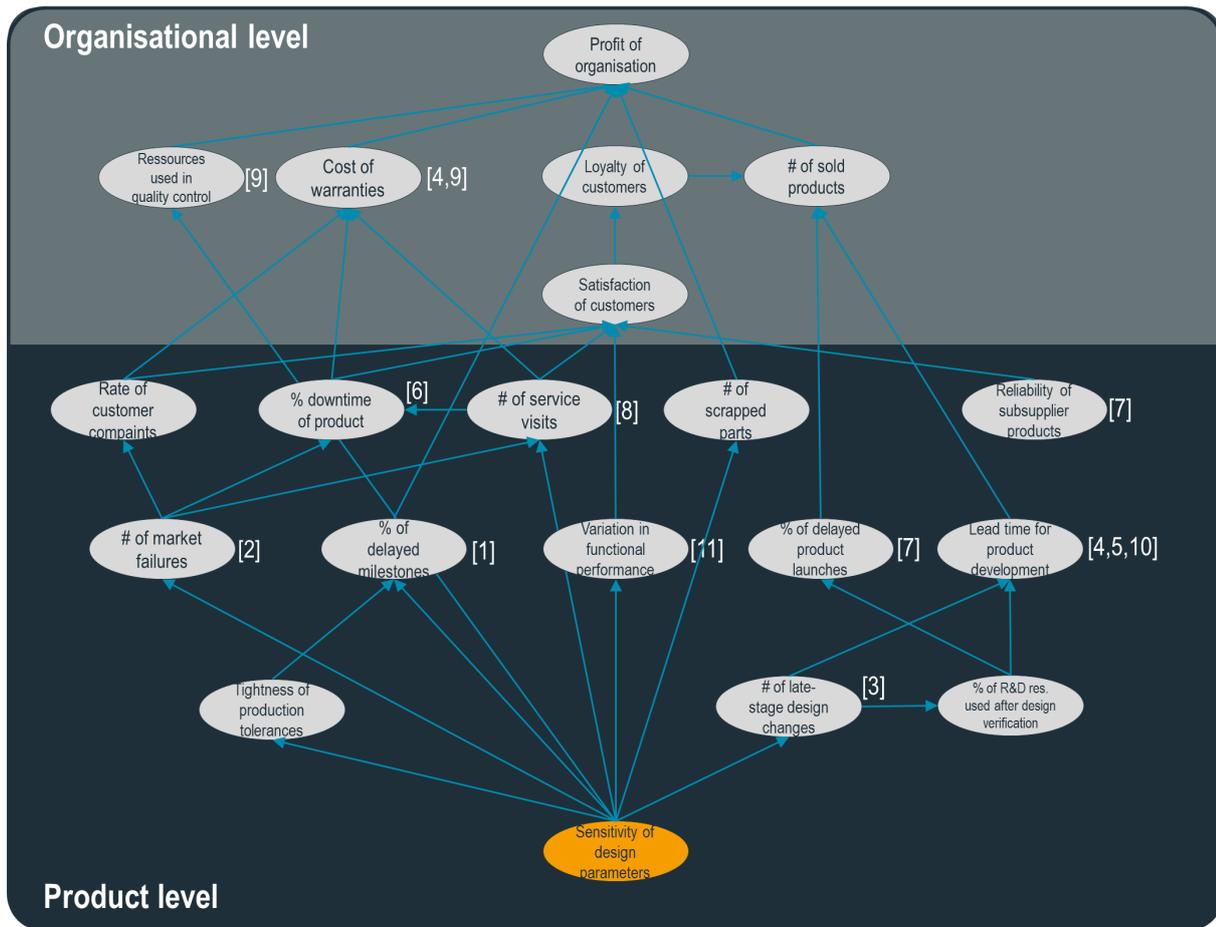


Figure 3. Robust Design Impact Model visualising the motivations and their associated impact factors identified in literature or in the case studies. Numbers in brackets [X] refer to the case numbers in Table 1.

The RD Impact Model in Figure 3 contains a structured overview of the factors related to RD, i.e. if RD was implemented, which factors in the organisation would potentially be impacted. An organisation wishing to improve factors that are included in the Robust Design Impact Model would thus benefit from implementing RD. Therefore, if an organisation assigns high importance to one or more of the impact factors then it is concluded, that RD is applicable in that organisation.

4.2 Applicability Model

The impact factors in the RD Impact Model have a certain level of impact on the overall success of any given product or organisation. For example, the predictability of the launch date of a new product in a consumer electronics company may have an extremely high impact, as 40% of the annual sales are placed up to Christmas, and therefore a delayed product launch in January is a significant loss compared to a planned launch in November. The impact factors in Figure 3 are used as assessment

points or factors in the RD Applicability Model, which is presented in Table 2. The impact factors on the "organisational level" have not been included, because any company would claim that factors such as profit, number of products sold and customer satisfaction are important. In the RDAM, it is possible to rate each factor on a scale from 'low impact' to 'high impact' based on the degree of impact the factor has on the overall success of the project or organisation. The impact scale also includes a description and examples of why each of the given impact factors may or may not be important, which can support the organisation in defining the correct impact levels. The results of the assessment of the importance of the impact factors can stand alone, but if data is available, it can also be extended to include the occurrence of each of the factors. An example of this is shown in figure 4. It is the intention that this figure can be used for defining and scoping a subsequent Robust Design project, by suggesting relevant focus areas and performance metrics.

Table 2. Robust Design Applicability Model Factors from the Impact Model are applied as assessment points. Robust Design is applicable if any of the factors in the table have a high impact on the success of the product or organisation.

ID	Factor	1 - Low impact	5 - High impact
1	Launch date precision	Launch dates have minor influence on profitability, e.g. due to long market life, lack of competitors, lack of technological edge	Launch dates highly influence profitability e.g. due to seasonal sales, a small market lifetime, or products being part of a larger engineering system (e.g. automotive).
2	Milestone precision	Minor importance, e.g. single-project or small organisations.	Delayed milestones cause major disruptions in the organisation planning e.g. in large organisations or organisations with large development portfolios. Key resources become tied up, affecting other projects.
3	Late-stage design changes	Low importance, e.g. due to in-house production, production-on-demand, simple or no tooling.	High importance, due to e.g. costly production tools (e.g. moulds), large inventories, long production lead times, complex supply chains
4	Customer complaint rate	Customer complaints have a minor impact due to e.g. easy complaint handling or low cost of replacement and service	Customer complaints have a high impact due to e.g. costly complaint handling, high brand expectations, or high replacement costs.
5	Development lead-time	Minor importance, e.g. if R&D costs constitute a minor share of overall product cost, markets with slow technological development.	Major importance e.g. due to R&D constituting a substantial share of overall costs, fast moving technological development in the market, fast moving market needs & expectations
6	Scrap rate	Scrap rates have little or no effect on the profitability of the organisation.	Scrap rates strongly affect the profitability of the company, e.g. due to high component costs or small profit margins.
7	In-market failure rate	Minor importance due to e.g. disposable single-use products, low-cost products, low customer expectations.	High importance, due to loss to brand value, cost of recalls, cost of replacement, safety aspects.
8	Variation in functional performance	Minor consequences of variation in performance, e.g. low-cost products.	High precision demands (e.g. measuring equipment, high-end products and medical devices).
9	Downtime of product	Uptime has little importance, e.g. for low-cost and disposable, single-use products.	Uptime extremely important due to e.g. quality agreements, safety issues (e.g. wind turbines and airplane engines).
10	Reliability of products/components from sub-suppliers	Minor impact, e.g. due to liability agreements, outsourcing of non-critical components or lack of outsourcing	Major impact due to e.g. outsourcing of complete product development project, liability agreements, or outsourcing of critical components
11	Tightness of production tolerances	Minor impact, e.g. due relatively low cost of components, low production volumes, or ease of adjustment during production	High impact, due to e.g. high production volumes, tooling with no adjustment options, or expensive components.
12	Service visits	Service visits have minor impact due to e.g. short distance to customers, low production volumes, high serviceability, disposable/single-use products, and mandatory service schedules	Service visits have major impact due to customer expectations, long distance to customers, complex serviceability, high production volumes, and long market life
13	R&D resources used after design verification	Minor impact due to uniformly skilled engineers, simple resource re-allocation, high profit margins, and flexible supply chain.	Major impact due to senior engineers being needed for conceptual work on other projects and sensitivity to budget overruns.

4.3 Assessment

The assessment of the organisation can be done as either a self-assessment or an external assessment by e.g. a consultant. It is the intention of the model to allow for a fast and efficient assessment, taking no more than an hour. However, knowledge about the importance of the factors does require a relatively holistic view on the organisation's market situation, financial setup, service requirements etc. so the assessment is expected to be carried out at managerial level.

4.4 Scenario

The Robust Design Applicability Model (RDAM) can be used in various scenarios:

1. As an ongoing assessment of quality related initiatives in the organisation, in order to create a common picture of factors of importance for the organisation. Especially in organisations with large differences in the types of products in the portfolio, it may be beneficial to make an applicability assessment prior to each new project, to define the necessary level of RD related activities for the given project.
2. Prior to launching a quality improvement initiative, in order to become clearer on the main drivers for the project and to create a common understanding of the objectives. Specifically, the RDAM can clarify whether RD can be expected to create an impact on the key factors, i.e. the factors that are important to the organisation.

4.5 Interpretation of the results

The Applicability Model does not result in Metric(s) as such, but it can be visualised in different ways to show which factors are important to the organisation. Furthermore, the model can support the creation a common language and a frame of reference for discussing the importance of factors related to Robust Design within the organisation. It is also important to note that it is not the average score that is important to the applicability. What is more important is whether or not any specific factor has on the model has high impact on the project or organisation. If at least one factor has a high impact on the performance of the organisation, RD is applicable and should be taken into consideration as a means of improvement.

4.6 Case example

To enhance the understanding of the RDAM, an assessment of a case organisation is presented in Figure 4. The assessment is based on a real manufacturing company that develops and assembles high-end office furniture such as height-adjustable desks and chairs. Production volumes are small and the components are expensive and hence material costs constitute a significant part of the unit costs, which makes the frequent scrapped parts relatively costly. Most of the sales are concentrated around two annual furniture fairs and there is a history of delayed product launches, which have resulted in having to turn down potential customers that were interested in buying after having seen the products on the furniture fair. Although it is a small organisation, it is a high-end brand with clients spread all over Europe, and hence the service visits, which happen to approximately 5% of the products, are costly.

The assessment of the case company was carried out by the chief engineer in 20 minutes using knowledge readily available to him. Based on the results, it is seen that several of the RD-related impact factors are identified as having a high impact as well as a high occurrence level, making RD likely to be applicable in this company. Furthermore, the results indicates potential metrics to be used as drivers and effect measurements in a subsequent RD implementation in the company. In this case, scrap rate, number of service visits and launch date accuracy would be good metrics to use.

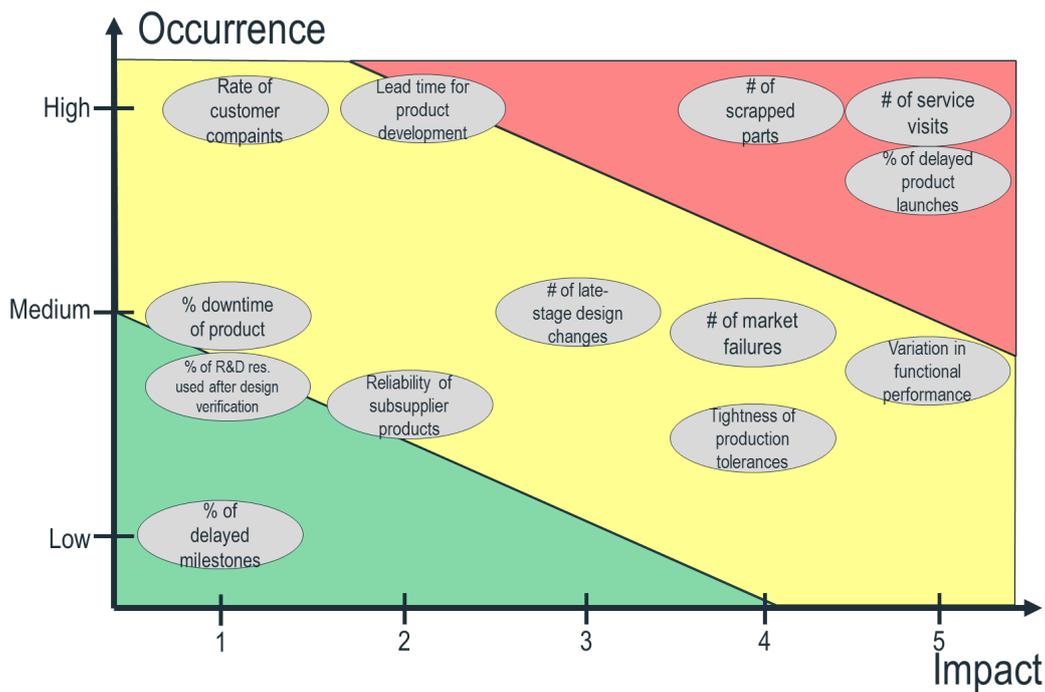


Figure 4. An example of the results of a RD Applicability Assessment in a small office furniture manufacturer. Several RD-related impact factors are identified as having a high impact and high occurrence rate, indicating that RD is applicable in the organisation

5 DISCUSSION

The **value** of the RDAM lies in its ability to identify whether or not RD is applicable for solving the issues of a given organisation. This increases the chance of using the right tool for the right problem, but the process of identifying the key factors also acts as a way of creating a common language and increases self-awareness in the organisation. Although the RD Impact Model is only used a stepping stone for deriving the RDAM, it is believed that the Impact Model itself also can contain valuable insights for an organisation, because it shows the path of impact factors all the way from the parameter sensitivity to the profit of the organisation. The link from parameters to profits can be used to create a shared understanding for the organisation. Furthermore, relevant metrics and targets can be set for each of the impact factors, such that the success of a RD initiative can be measured. Finally, the RDAM contributes by providing a simple overview of the potential benefits of RD - and by showing in the impact model how sensitive designs are linked to the profit and success of the company.

The RDAM has certain **limitations**. It is not necessarily exhaustive in the sense that it includes all relevant and potential impact factors of RD. Therefore it would be natural to extend and consolidate the model as more cases and literature become available. Furthermore, the current scale in the RDAM does not contain any metrics, which can make it challenging to define whether e.g. "launch date precision" has a medium or high impact. The scale could be extended by adding such metrics, which would allow for a more precise assessment. This could also result in the assessment taking more time, because extra analysis work would be required to derive these metrics for the organisation and this would conflict with the original idea of creating a fast and efficient assessment tool. Finally, RD obviously has certain overlaps with other quality frameworks such as Lean Six Sigma and Design for Manufacture/Assembly etc. It should therefore be considered, whether other frameworks than RD are also applicable for addressing the important impact factors.

As to **further research** it is suggested to verify the model. Currently, the model indicates that if certain factors, e.g. launch date precision are important, then RD methods are applicable tools for impacting these factors. A follow up study could close the loop and verify that RD actually did affect the relevant key factors for each of the mentioned cases.

6 CONCLUSION

The purpose of this paper was to answer the question of how an organisation can identify whether RD is applicable. By analysing empirical data from various RD cases from multiple branches in the European industry, relevant impact factors of RD have been identified and applied as assessment points in an applicability model. The Robust Design Applicability Model (RDAM) fills a literature gap within engineering design theory on RD and it represents a simple and operative tool to identify the relevance of RD. Together with a reliability maturity assessment (e.g. IEEE1624) and relevant reliability performance metrics, the RDM constitutes a comprehensive set of information that can support the decision as to the extent of robustness and reliability related activities to be required in a specific project or the overall organisation. The assessment can be performed internally or by a RD maturity mapping expert. In addition to identifying the applicability of RD, the model can create a common understanding in the organisation about the importance of specific impact factors and the connection between low-level factors (such as parameter sensitivity) and high-level factors such as warranty costs and profit.

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