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Evaluation of the Impact of Collaborative Research on Robust Design Methodologies: A Large Scale Empirical Case Study with an Automotive OEM

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Abstract

The evaluation of impact of collaborative research on robust design methodologies and methods is important to both academic and industry stakeholders. This paper introduces a framework for impact evaluation which combines the broader framework adopted for the academic research impact assessment with the organisation viewpoint centred on business results, process improvement and product development teams capability improvement. A large scale empirical study conducted with evidence from technical reports on workplace projects from an automotive OEM proved the validity of the proposed framework.

Keywords: robust design, design methods, design evaluation

1. Introduction

1.1. Evaluation of impact of design methodologies as a research challenge

Academic research in design theory and methodology (DTM) (Tomiyama et al., 2009) generally aims to explore ways of approaching and handling design problems or tasks to achieve a specified outcome (Wallace 2011). Ultimately, the aim is to provide the industry with means for developing better products in a more efficient and effective manner, through studies focused on "how" designers, teams and organisations approach and complete a diversity of design tasks, and how this can be improved by better methodologies, methods and tools (Tomiyama et al., 2009; Blessing & Chakrabarti, 2009). The evaluation of design methods in relation to their take-up in practice generally revolves around the high-level criteria defined by Blessing & Chakrabarti (2009) of usefulness, applicability and usability.

There is wide recognition that design methods, especially the ones which have been around for a long time such as FMEA, QFD and DFA, have an important impact on product success, effectiveness and efficacy in new Product Development (PD) projects (Booker, 2012). However, evidencing this impact in a traceable way to the underpinning DTM research is difficult and challenging (Gericke et al, 2020; Daalhuizen 2014). Many studies (see for example Nijssen & Frambach, 2000; Birkhofer et al., 2001, Müller et al., 2007; Yeh et al., 2010; López-Mesa & Bylund, 2011; Booker, 2012; Gericke et al., 2017) have pointed out that the implementation, dissemination and use of design methods in industry is limited and low despite their potential to improve the product development process. This is explained to a large extent by the fact that industry focus is on using "methodologies to achieve concrete goals" (Tomiyama et al, 2009) to support effective problem solving for routine design tasks, over more abstract methods, which are widely taught as they have value for engineering design knowledge and skills development. Other factors discussed include the lack of focus on design methods implementation, considering the broader behavioural and organisational aspects of the product development organisations, and the poor follow up and evaluation, as researchers tend to focus on “success stories” which might not be truly useful in an objective evaluation of methods (Tomiyama et al, 2009; Blessing & Seering, 2016). Collectively, these arguments support the point made by Gericke et al (2020) that, while there is no doubt that research into methods and methodologies have an impact to industry (e.g. common tools and methods used in industry, from CAD to Six Sigma and FMEA, have traceable roots to design research), a much longer timeframe is required to gauge the real-world impact to practice, given the complex dependencies of success with organisational factors within a complex PD organisation.

1.2. Background to the industrial context of this research

From an industry point of view, the adoption and implementation, as well as the overall governance of methods and tools in a PD context is integrated within the continuous improvement processes and cycles within the organisation. Companies tend to invest in the continuous improvement of tools and methods, including their adoption and implementation, in cycles that are aligned with the organisation business dynamics (Repenning & Sterman, 2001). Long term collaborative engagement between companies and academia affords opportunities for academic research to be aligned and integrated with the industry needs for the continuous improvement of PD design methods and tools. This paper reflects on an university-industry collaboration spanning over 25 years, involving several global automotive OEMs, focused on methodologies and methods for robust design in automotive product design and development. The dynamic of this collaboration over this extended timeframe has seen several cycles of research and development, summarised below:

a) **Industry-based research**: the initial phase focused on consolidating and embedding "Engineering Quality Improvement" (Henshall, 1995) methodologies and methods within automotive PD engineering, with within-industry research projects aiming for best practices and innovating in the way the methods can be adopted to enhance quality and robustness in PD.
b) **Academic-led research**: the deep embedded collaboration on continuous improvement of robust design methods within automotive PD has enabled the identification of more fundamental challenges (in particular around the functional basis for complex systems design analysis early in PD, supporting comprehensive robust system design requirements, and the coherence and integrity of the information flow across methods leading to the comprehensive robust design verification plan). These challenges have been addressed through academic-led research, including the development of new methods, designed to fit with the existing robust design methods ecosystem in industry use, within a "Failure Mode Avoidance" (FMA) methodology (Campean et al, 2013). The continuous exchange with industry, including collaboration on case studies to prove the methodologies, and the extensive training of methods through continuous professional development courses, facilitated the transfer of methods.
c) **Industry-commissioned academic research**: the drive for innovation with vehicle control "features" (e.g. advanced driver-assistance systems, safety and refinement) in automotive systems design in the last decade has raised the need to scale up the FMA methods to assist feature development within the context of the systems engineering methodology and tools increasingly adopted by automotive OEMs. This is significant given the increased interdisciplinary complexity of PD teams responsible for the design integration and design assurance of both software and physical systems. The commissioned collaborative research (two projects with two global OEMs focused on Systems Engineering Design Excellence) saw academic researchers working with industry specialists on industry based validation case studies, with training developed jointly to facilitate the adoption of the methods.

1.3. Research Aims and Contribution

This paper discusses the evaluation of the impact of a methodology developed through collaborative research with a global automotive OEM. The research focused on updating of the FMA methods and methodology to support interdisciplinary teams early in product development within a feature engineering context, including the coherent integration with the systems engineering workflows and tools early in the PD process. While the Company's approach to FMA was relatively mature, with established governance of methods and tools for robustness and design assurance, the application of the FMA methods was perceived as being limited to physical systems, not easily translatable to control and software features early in the PD phases (research and advance product creation). Additionally, the FMA methods were not integrated with the systems engineering workflows, which were at the time at an initial stage of development / adoption. The collaborative research project (2014-2017) considered a diverse range of case studies and use cases for the application of the methods as part of the validation, with a view to also ensure that the updated methodology delivers the stated requirement to facilitate "engagement throughout the organisation to deliver right first time for the whole product lifecycle". The adoption and propagation of the research outcomes within the PD organisation was facilitated through updates to internal processes and methods, and learning interventions (Campean et al, 2017) deployed through both internal training (focused on practitioner skills) and external academic led and accredited training focused on developing expert practitioners to lead the adoption and facilitation of methods in the workplace. As the company has invested significantly in this development (including the cost of commissioned research, the time of engineers participating in the research, the cost of training delivery and the cost of the significant time commitment for engineers to participate in the training), evaluating the impact to the organisation is an important return-on-investment consideration. From an academic point of view, the evaluation of the impact of research is also important, in particular as the evaluation of academic research quality is increasingly focused on impact to society. However, as discussed earlier, the evaluation of the impact of designed methodologies is still a significant research challenge.

The aim of this paper is to present a contribution towards addressing the challenges discussed relating to the evaluation of the impact of design methodologies. A framework is introduced for the evaluation of the impact of collaborative industry-academia research on design methodologies and methods, and its validation discussed in conjunction with an empirical evaluation study carried out with the OEM.

The structure of the paper includes a review of related research on methods transfer to industry and evaluation of impact, followed by the introduction of the proposed methodology for impact evaluation, presentation of results and analysis from the case study, and discussion and conclusions.

2. Review of related research

2.1. Transfer of methods to industry: consideration of frameworks and factors

It is widely reflected that the transfer of knowledge between academia and industry should be considered from both short- and long-term perspective (e.g. Beckmann et al 2014). On-going cooperation and collaboration between academia and industry defines the long-term perspective of knowledge transfer, and it is recognised in many studies as key for the successful transfer of methods (Sheldon & Foxley, 2003; Sandberg et al., 2011; Wohlin et al., 2012 and Becattini et al, 2016). While the implementation of a specific method is often regarded as a short-term transfer action, the way in which methods are implemented in companies plays an important role in the successful long term take-up and usage of the methods. Geis et al. (2008) have explored the challenges with the transfer of new methods in general, from the perspective of interaction, planning and usage of methods, and have established a framework for a transfer model based on four pillars: (i) simplification of methods to facilitate their application in practice; (ii) adaptation of methods to fit with the context of the deployment; (iii) internal promotion of the methods; and (iv) specific training of methods. This reference model bridges the gap in terms of objectives and focus between design research in academia and design practice in industry. As suggested by Ponn (2016), the former focuses on the academic value (i.e. searching for new contribution to the body of knowledge), while the latter focus on practical value (i.e. searching for methods that work and can be put to use).

Many researchers have studied success factors and barriers for the transfer of methods and tools to industry. Jagtap et al. (2014) have assembled a framework that highlights the importance of the interplay between the attributes of the methods, both positive (e.g. user-friendliness) and negative (e.g. poor compatibility with the company processes), the importance and timeliness of the method development process (e.g. taking into account the actual needs of companies), and the aspects of the practice in relation to the use of the methods (e.g. attitudes of users). Guertler et al (2018) have discussed the importance of effort and quality of data collection associated with a method, emphasizing "applicability in industry" as a key aspect of the performance requirements. The interview study of Hiort et al. (2014) focused on the practitioner requirements, highlighting factors related to the qualities of the methods, including formalisation and prescription, their usability and applicability in a specific industrial context, and the likelihood of spreading through active implementation. The interview study of Beckmann et al. (2014) considered the knowledge of the participants about a particular set of methods, highlighting the importance of training approach and the role of organization management support.

Barriers to the transfer of methods to industry have been discussed by many researchers (e.g. Birkhofer et al. (2005), Eckert and Clarkson (2005), Badke-Schaub et al (2011) and Gericke et al (2017)). Some studies, like the interview studies of Beckman et al (2014) and Hiort et al (2014), have discussed concurrently the success factors and barriers for methods transfer, which is useful as it highlights the importance of context (of the product development process as well as the organisation and culture) on the actual impact of some factors. Stetter and Lindemann (2005) and Wallace (2011) discussed that the implementation of methods in industry takes time, as companies are under pressure to develop and deliver products, and therefore the observation of impact and benefit is delayed. Taking an industry view-point, Stetter (2016) has emphasized that evaluation of impact of design methods research in a real world industrial product development context is also affected by the inherent complexity of the design and development process for complex systems – which unfolds over a much longer periods of time and requires the concurrent and interconnected deployment of a large and varied mix of methodologies and methods, as well as the organisational effectiveness of the product development organisation. This prompts to difficulties to establishing the timescale for evaluation of effects (in particular in relation to objective metrics used by industry associated with commercial results and process efficiency and effectiveness metrics), as well as the a posteriori attribution of success to a specific intervention or conversely, the likelihood of seeing an overall effect given an otherwise successful intervention.

2.2. Methodologies for the evaluation of impact of design methods in industry

Bender et al (2002) discussed that common methods for the empirical analysis of design process to evaluate the impact of design research revolve around (i) observation studies on either individuals or groups; (ii) interviews and surveys with individuals and groups; and (iii) evaluation of generated outputs from the application of the method. Given that observation studies require a controlled environment, they are in general less feasible for the broader evaluation of impact and in particular in conjunction with industry practice. Most studies on the evaluation of impact of the transferred method to industry have been based on surveys and interviews, and in some cases evaluation of case studies of the application of the methods. Several studies have used surveys for a broad evaluation of the design methods and tools used in industry and their impact, often focused on a specific country. For example, Araujo et al (1996) explored the utilisation of methods in product design across industrial sectors in the UK using a combination of survey and interviews. Several similar studies have followed reporting the utilization of various product development tools and methods in specific countries. The more recent study of Yutaka et al (2017) provided a useful view of the evolution over time based on a follow-up study, which also included an evaluation of the effectiveness of methods and tools. Similarly, Laing et al (2020) have reported on a large survey to evaluate the impact of Model-Based Systems Engineering on verification activities in current industrial practices. However, Baciotti et al (2016) have discussed that questionnaire-based surveys do not really allow for the extent to which academic research really addresses the needs of the companies to be probed, and proposed an ethnographic approach, based on a closer relationship with enterprises. This reinforces the importance of the close collaboration between academia and industry over the development of specific methods (Beckman et al, 2014).

3. Methodology for Impact Evaluation

3.1. Proposed Framework for the evaluation of Impact

While the review of the related literature has shown a rich field of studies that have made valuable contributions with different aspects, there is still a lack of a clear and comprehensive set of criteria and

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metrics that can be applied to evaluate the impact of design methods research to industry. Given that business results take a much longer time to yield, the evaluation of the impact of design methods research to industry should take a much longer timeframe as reference. Stetter (2016) has also discussed that given the complexity of systems designed and also the growing complexity of the PD, makes it very difficult if not impossible to evaluate or attribute the impact of a method in relation to the achieved business results. Hicks (2016) illustrated a similar effect through a deep dive evaluation of 22 design-led academic research impact cases submitted to the UK REF 2013 (Research Excellence Framework). This showed that design research that resulted in a new product had greater reach, and were better able to substantiate the impact with quantitative measures, compared to design process led research.
The approach taken by the research team was to anchor the impact evaluation framework on two pillars:

1. The UK REF 2021 framework for impact evaluation of academic research, which adopted a broad approach to the consideration of areas of impact, with examples of types of impact and possible metrics and indicators of the impact for each area. The relevant areas of impact from the REF 2021 guidelines include: A4 - impact on commerce and the economy; A6 - impacts on production; A7 - Impacts on practitioners and delivery of professional services, enhanced performance or ethical practice; and A9 - Impacts on understanding, learning and participation.
2. The business / organisation viewpoint: while there was a broad recognition that "soft" benefits (associated with individual and teams skills gains) were important to the organisation, discussions with OEM stakeholders centred on identification of categories of benefits to the organisation where tangible evidence can be identified as impact of the research and the subsequent transfer. The main categories identified included business results, process improvement in the PD organisation, and PD teams effectiveness.

Collectively, the academic and industry team have considered both the REF Impact Framework and the business viewpoint, and have agreed on the impact evaluation framework presented in Table 1, where the definition of the types of impact draws on the REF definitions and examples, and the example evidence is defined in a way in which evidence in the form of examples can be searched.

Table 1. Impact evaluation framework

Type of impact	Example evidence
Business Results: Evidence of improved cost effectiveness, avoidance of negative outcomes, enhanced organisational performance	Costs Avoided/Saved
	Quality Improvement
	Time Saved
	Customer Experience Enhancement
Process Improvement: Evidence of enhancements to processes and practices leading to enhanced PD effectiveness	New Failure Modes
	New/Improved Process
	New Standards
	New Requirements
	New Test cases
	Improved Efficiency
	Supplier Improvement
PD Teams Capability Improvement: Enhanced knowledge and effectiveness of teamwork in PD	Organisation core knowledge
	More Effective Team Working
	Improved Communication

3.2. Methodology for Quantitative Evaluation of Impact

The body of evidence available for conducting the impact evaluation consisted of the technical reports submitted by the engineers that have participated in the external academic led 5 days training module developed as an outcome of the collaborative research project. The course was made available organisation-wide, part of a broader postgraduate "technical accreditation scheme" (Lopes, 2013) run by the Company in conjunction with multiple University partners. Each engineer attending the training module was required by the Company to complete a workplace based project to apply the methodology within a team environment and in the context of a current engineering problem, with oversight from

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both line management and subject matter experts, and guidance from the academic research team. The workplace project timescale was 6-8 months, and each engineer had to submit a technical report for the academic accreditation, in addition to any internal deliverables to the local team.
A sample of 100 technical reports were selected for the impact evaluation exercise. In order to ensure objectivity of the study, the selection was based on the submission date: i.e. the first 100 technical reports submitted after the launch of the module were selected for the deep-dive analysis. These reports were submitted between July 2017 and March 2020, thus covering a substantive period of time after the end of the research project – sufficient to allow reflection on the longer term impact to engineering practice.
The first phase of the study was predominantly quantitative, carried out by the academic team, and focused on the evaluation of:

- The distribution of projects across engineering centres of competence (CoC), and phases of project / product development lifecycle;
- The usage of methods across projects / project areas, and the integrity of the methodology deployment, in particular the use of methods in the recommended sequence to deliver the robust flow of information from function analysis to robust design verification.

The second part focused on the evaluation of the impact to the business, based on the evidence in the technical reports, against the impact framework outlined in Table 1. In order to ensure objectivity of the evaluation in relation to the business viewpoint, the assessment was carried out by the two experienced engineering managers from the Company, bringing a sharp insight into the assessment of value to the business from each project.

4. Results and Analysis

4.1. Distribution of Projects with Areas of Engineering Competence

Figure 1 illustrates the distribution of the technical reports analysed with the CoCs in the PD organisation, showing that all competency areas have been represented in the analysis. Body Engineering and Powertrain have the highest number of projects, and overall the distribution of projects is reflective of the distribution of engineering workforce in the PD organisation. While the design methodology was primarily targeted to deployment in the early product design phase, given that it was part of the "engineering and process excellence" competence area, it was open to participation from manufacturing and field operations engineers. Figure 1 also provides a cross analysis of the normalised distribution of the number of projects analysed with the PD phase (Concept – including advanced research; Product Creation; System Integration; Assembly; Service operations). This shows a consistent pattern of distribution across the main centres of engineering competence (Body, Powertrain and Vehicle Engineering), with most projects focused on the early phases of product design. Chassis have a smaller proportion of projects in the early phases of product development, which could also be associated with the lower overall proportion of projects in the sample. Projects focused on Electric Vehicles show a higher concentration of "concept" phase analysis, reflecting the focus on R&D in this area. Projects based in the Engineering Laboratories are all focused on concept methodology development, whereas manufacturing and operations based projects are, as expected, biased towards assembly and field / service operations. In relation to the system level of the analysis, Figure 2 illustrates the normalised distribution of projects across the systems levels of analysis, showing that most projects are targeted at a subsystem level. Figure 3 illustrates the analysis of the system level for projects across different PD phases. This analysis shows that in concept phase the majority of projects focus on a system level, whereas in product creating and system integration PD phases most projects are focused on a subsystem level. A total of 28 projects (28%) have approached the analysis across more than one level.

4.2. Analysis of usage on methods on projects

Figure 4 illustrates the overall usage of tools across the projects / technical reports, based on data collected from the individual review of each project. This shows that the tools traditionally used within the PD organisation have been widely employed: Boundary Diagram – 94%, FMEA 91% and P-Diagram 73% of the projects, respectively. However, the new function analysis tools have also been

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consistently employed in the majority of projects across all areas (Systems State Flow Diagram, SSFD – 72% and Interface Analysis 82% of projects, respectively). To further substantiate the integration between the tools within the new methodology in terms of the consistency of the information flow across the tools, Figure 5 illustrates the usage of tools feeding into the FMEA. This shows a very high usage of the function analysis tools, i.e. 73% of the FMEAs have carried out a SSFD function analysis; and 88% and 84%, respectively, have used an Interface Matrix and Interface Table. This shows a highly consistent application of the methodology across the projects, which is a significant improvement over the historic process conformance.

Distribution of projects		Concept	Product Creation	System Integration	PVT	Assembly	Service Operations
22%	Body Engineering	36%	23%	32%	9%	0%	0%
9%	Chassis Engineering	11%	11%	44%	22%	0%	11%
17%	Vehicle Engineering	35%	35%	29%	0%	0%	0%
20%	Powertrain	35%	30%	35%	0%	0%	0%
11%	Electric Vehicles	55%	27%	18%	0%	0%	0%
5%	Engineering Laboratories	100%	0%	0%	0%	0%	0%
11%	Manufacturing	9%	9%	9%	27%	45%	0%
5%	Operations	20%	20%	0%	0%	0%	60%
	Number of projects	35	23	26	7	5	4

Figure 1. Analysis of distribution of projects with engineering CoC areas and phases of PD

	System	Subsystem	Component	*Multiple levels*
Body Engineering	50%	77%	27%	*45%*
Chassis Engineering	33%	78%	11%	*22%*
Vehicle Engineering	59%	71%	0%	*29%*
Powertrain	60%	75%	5%	*35%*
Electric Vehicles	36%	45%	36%	*18%*
Engineering Laboratories	60%	40%	20%	*20%*
Manufacturing	27%	64%	18%	*9%*
Operations	40%	60%	0%	*0%*

Figure 2. Level of system analysis Vs engineering competence area

	Concept	Product Creation	System Integration	PVT	Assembly	Service Operations
System	63%	43%	42%	14%	40%	50%
Subsystem	46%	91%	81%	86%	40%	50%
Component	17%	9%	19%	14%	20%	0%
Multiple level	*26%*	*35%*	*38%*	*14%*	*0%*	*0%*

Figure 3. Level of system analysis Vs Phase of PD

Further analysis of the tools usage is presented in Figure 6 as heatmaps (based on normalised percentages) of the differential usage of tools on projects across the PD centres of competence areas, PD phases, and the system level of analysis. A key overall reflection across these heatmaps is that the pattern of the distribution of the usage of tools is reasonably consistent across the different project areas, phases and system levels. The systems engineering specific methods (Use Case Analysis UCA/Use Case Diagram and Sequence / Activity diagram) usage was prevalent in concept and advanced project creation projects, but significant use was also seen in projects carried out on current vehicle programmes.

4.3. Evaluation of Benefit to Business and PD Organisation

A deep dive review of the technical reports based on projects was carried out to identify the benefits that were achieved from the project-based implementation of the methodology. Each individual project technical report was reviewed in turn, with a view to extract the main benefit for the company. This was not always a straightforward task, as most of the technical reports focus on the technical aspects of the methodology deployment and lessons learnt, without explicitly recording business benefits.

The benefits were identified and classified based on the impact framework shown in Table 1. A further quantitative analysis was carried out on the statistics of benefits identified. In total, 242 examples of evidenced individual benefits were identified from the 100 projects reviewed, with a distribution across the 14 categories of impact as shown in Figure 7. In relation to the impact framework considered, the analysis in Figure 7 shows that most of the reported benefits are on "Process Improvement" (around 60% of all the benefits reported, and an average of 1.44 benefits per project), and "PD Teams capability Improvement" (nearly 30% of the benefits, with 71 individual benefits identified). Overall, this defines a significant impact on the PD Process Effectiveness with strong evidence on leading impact indicators.

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However, 24 out of the 100 projects have identified at least one directly quantifiable business result benefit (costs saved, quality improvement leading to expenditure avoidance or business loss, time and resource expenditure saved, actions for customer experience enhancement), which is a significant result.

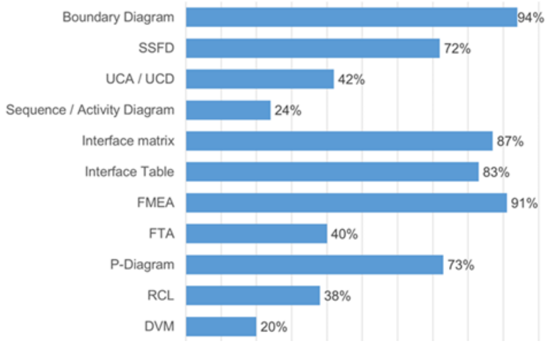


Figure 4. Overall analysis of methods usage in projects

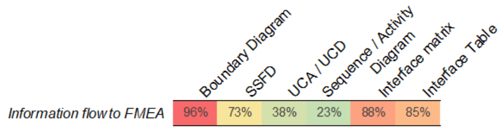
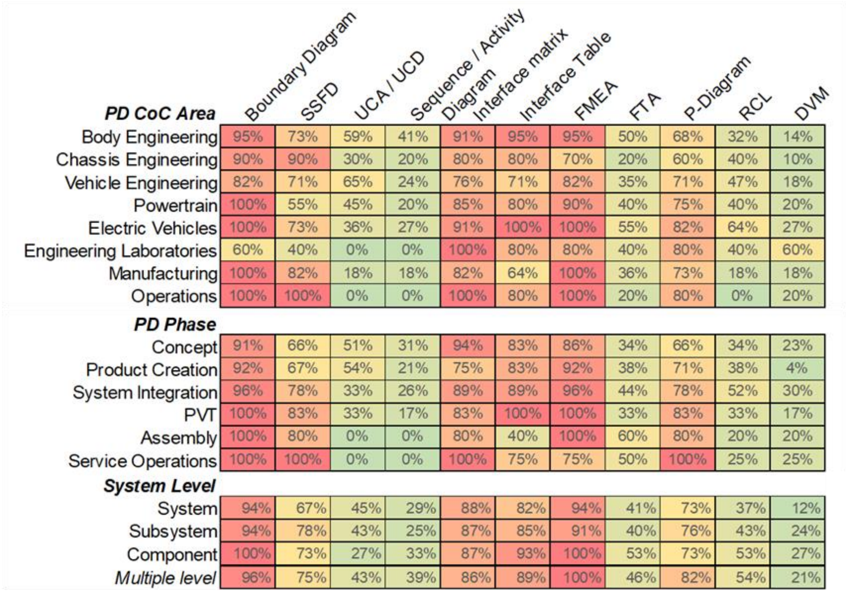


Figure 5. Heatmap analysis of integrity of the information flow



PD CoC Area	Boundary Diagram	SSFD	UCA / UCD	Sequence / Activity Diagram	Interface matrix	Interface Table	FMEA	FTA	P-Diagram	RCL	DVM
Body Engineering	95%	73%	59%	41%	91%	95%	95%	50%	68%	32%	14%
Chassis Engineering	90%	90%	30%	20%	80%	80%	70%	20%	60%	40%	10%
Vehicle Engineering	82%	71%	65%	24%	76%	71%	82%	35%	71%	47%	18%
Powertrain	100%	55%	45%	20%	85%	80%	90%	40%	75%	40%	20%
Electric Vehicles	100%	73%	36%	27%	91%	100%	100%	55%	82%	64%	27%
Engineering Laboratories	60%	40%	0%	0%	100%	80%	80%	40%	80%	40%	60%
Manufacturing	100%	82%	18%	18%	82%	64%	100%	36%	73%	18%	18%
Operations	100%	100%	0%	0%	100%	80%	100%	20%	80%	0%	20%
PD Phase											
Concept	91%	66%	51%	31%	94%	83%	86%	34%	66%	34%	23%
Product Creation	92%	67%	54%	21%	75%	83%	92%	38%	71%	38%	4%
System Integration	96%	78%	33%	26%	89%	89%	96%	44%	78%	52%	30%
PVT	100%	83%	33%	17%	83%	100%	100%	33%	83%	33%	17%
Assembly	100%	80%	0%	0%	80%	40%	100%	60%	80%	20%	20%
Service Operations	100%	100%	0%	0%	100%	75%	75%	50%	100%	25%	25%
System Level											
System	94%	67%	45%	29%	88%	82%	94%	41%	73%	37%	12%
Subsystem	94%	78%	43%	25%	87%	85%	91%	40%	76%	43%	24%
Component	100%	73%	27%	33%	87%	93%	100%	53%	73%	53%	27%
Multiple level	96%	75%	43%	39%	86%	89%	100%	46%	82%	54%	21%

Figure 6. Heatmap analysis of usage of tools across CoC, PD phase and System level of analysis

5. Discussion and Conclusions

The main contribution of this paper is the introduction of a framework for the evaluation of impact of design methodologies to industry, validated through a comprehensive case study set within the context of a long-time collaboration between a university and a global automotive OEM. The analysis of the evidence has demonstrated good penetration of the tools across the PD organisation, providing evidence of persistent use of the methods. While this provides evidence for "usefulness, applicability and usability" (Blessing & Chakrabarti, 2009), it does not substantiate impact against either the REF2021 or the business benefits criteria. The deep-dive evaluation of benefits to the organisation, conducted against the impact evaluation framework introduced in Table 1 by experienced business leaders, has brought clear quantifiable evidence of impact, in terms of: (i) *business results*: 24% of the projects have identified at least one quantifiable benefit as costs avoided / saved, quality improvement, time saved or customer experience enhancement; (ii*) process improvement*: the vast majority of projects have resulted in greater integrity of the analysis and effectiveness in identifying new functions, new failure modes, defining new standards, new requirements, new test cases, implementing new/improved processes, ultimately leading to significantly improved outcomes for those projects; and (iii) *PD teams capability improvement*: a significant number of projects have highlighted capability improvement resulting from

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more effective team-working, improved communication and enhanced core knowledge. While time / effort required to deploy the methodology was often invoked as a barrier, the perception of increased team effectiveness by one third of engineers in the sample is significant. Without exception, all engineers appreciated the personal learning and skills gains, and most have also reflected on team learning - given the team context of the project application. With reported typical project teams of between 3-8 engineers, often involving external organisations, this provided good evidence of reach and sustainability.
The impact evaluation framework presented in this paper should have broad applicability. However, the methodology for collecting evidence in different collaborative contexts requires deeper consideration, based on the size of the organisation and approach to method transfer.

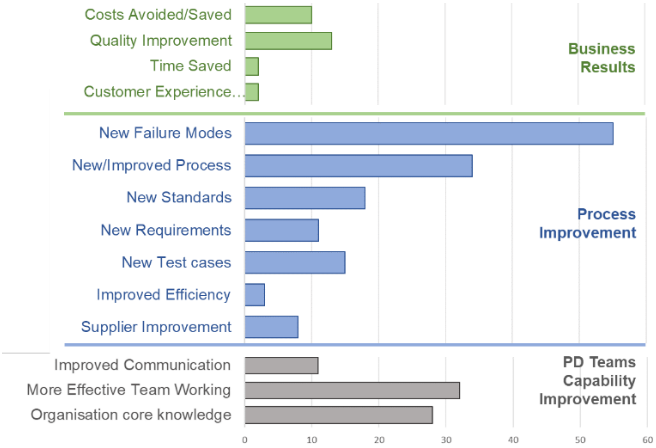

Figure 7. Quantitative analysis of benefits identified

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