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# The Use of Function Modelling Methods in Industry: Insights from a Large Scale Study with an Automotive OEM

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**Abstract**

This paper presents an evaluation study for the System State Flow Diagram function modeling framework based on a large-scale study with an automotive OEM. Technical reports are used to evaluate the usage of the framework within the organization. The paper also introduces a list of the type of problems that engineers are interested in in practical function modelling. The findings suggest that there is a widespread uptake of the framework across the organization and it supports the usage of relevant key engineering tools within the context of a broader model-based Failure Mode Analysis methodology.

*Keywords: functional modelling, product development, evaluation, introduction of methods in industry*

## 1. Introduction

Increased customer demands, environmental concerns and legislations are pushing product design and development organisations for the integration of a variety of functions associated with different disciplines into newly developed systems. The developed system can constitute completely a new product (i.e. it is developed from scratch) or a product with a direct predecessor such as the evolution of cars. Both cases require knowledge about functionality of the system which is necessary in the early phase of system development (Albers et al., 2019).

Pahl et al. (2007) introduced one of the most ubiquitous function modelling frameworks in the literature. Their framework provides the basis for many of the well-established modelling schemes in mechanical engineering literature, including Roozenburg and Eekels (1995), Stone and Wood (2000), Ulrich and Eppinger (2003) and Ullman (2010). The underlying principles of Pahl & Beitz`s flow based function modelling methodology have also been widely adopted in other disciplines beyond mechanical engineering: electrical engineering, mechatronic system development and Product Service System design literature (Eisenbart, 2014).

Function modelling provides a means of understanding of the system to be designed early in the so-called V-model (Forsberg and Mooz,1998; Graessler et al., 2018), with the left side of the V-model requires top-down cascade of functional requirements of the system. Function modelling makes the conceptual design process more systematic and guided by providing a set of rules for the reasoning about functional requirements of a system and relating these requirements to design elements that compound the final concept of the system (Pahl et al., 2007). This makes function modelling useful in the integration of design elements related to different disciplines early in the product design and development process, leading to the identification of design flaws early in the design process and, thereby, a reduction in the number of engineering changes (Webb, 2002; Hamraz, et al., 2015). Erden et al. (2008) suggest that function modelling promotes an enhanced communication within an organization whose departments are associated with a variety of disciplines. This is a big need during conceptual design (Badke-Schaub et al., 2011). The findings of Eisenbart and Kleinsmann (2017) across six product design and development organizations also point out the importance of function modelling in the early design stage through the integration of solutions developed in different departments, and in the communication of designers within and across engineering disciplines.

Various studies point out the weak dissemination and use of design methods in the product development process despite their potential to improve the product development process (Nijssen and Frambach, 2000; Birkhofer et al., 2001, Müller et al., 2007; Tomiyama et al., 2009; Yeh et al., 2010; Wallace, 2011; Booker, 2012; Gericke et al., 2017). The same fact applies to function modelling in particular. Despite its benefits in the design process mentioned earlier, the uptake of function modelling in practice is quite limited (Araujo et al., 1996; López-Mesa and Bylund 2011 and Tomiyama, 2013). Eisenbart and Kleinsmann (2017) suggest that the level of detail, complexity and the time required for the implementation outweigh the benefits of function modelling. Established function modelling approaches with a variety of interdisciplinary applications in the literature, such as System Modelling Language (SysML - OMG, 2019; e.g. Martin et al., 2015; Santos et al., 2017), present the same problem. Wolny et al. (2020) suggest SysML is too generic for some domain-specific tasks and lacking of operational semantics, while Herzog et al. (2012 point out that the sheer size of the language hampers its introduction in large organisations and they also mention difficulty in the modelling of large systems.

Yildirim et al. (2017) pointed out various problems with function modeling of complex systems based on a comprehensive review of literature, for example, not supporting top-down solution independent analysis, not being scalable across the levels of abstraction of the system and not providing a coherent link with customer requirements. They introduced the System State Flow Diagram (SSFD), as a rigorous framework for function modeling and representation methodology, to address these problems by establishing a rigorous academic basis and providing a systematic guidance to the practitioners in applying the methodology to practical problems.

As suggested by Tomiyama et al. (2009), there is a correlation between the concrete outputs created by a method and its widespread application. Several researchers have introduced a survey / review on the implementation of function modelling tools in practice. Eisenbart et al. (2016) introduced an analysis of the use of some functional modelling approaches at ten engineering companies. Their work provides an insight into the use of function modelling approaches in different disciplines and across with a specific reference to the main market of the companies and engineering disciplines, as well as the specific needs and preferences of practitioners. In connection with their work, the interview of Eisenbart and Kleinsmann (2017) with the participants from six companies reveals advantages and challenges of the use of shared function modelling (i.e. joint generation and subsequent usage of models) in design teams. Eisenbart et al. (2015 and 2017) also presented an evaluation study for the Integrated Function Modeling framework with practitioners in industry. They based this evaluation on questionnaires and open discussion with the aim of obtaining feedback on the framework's usefulness and applicability in practice. Grauberger et al. (2020) introduced the findings of the last 20 years of research on the Contact and Channel Approach based on categorised cases of application.

This paper aims to introduce the contribution of the SSFD function modelling method to a major automotive OEM in the UK based on the analysis of a range of technical reports completed for a technical course delivered by the authors. The type of problems that people from industry are encountered in practical function modelling are also explored in this context. By doing so, we intent to provide a different perspective on how to bridge a gap between the potential benefits of a function modelling method discussed in research and its widespread uptake in practice. The next section introduces the background to our research, while Section 3 focuses on the introduction of research methodology. Section 4 presents findings from the analysis of the reports, and Section 5 introduces a discussion and conclusions in relation to the findings.

## 2. Background

Collaborative works of the Bradford Engineering Quality Improvement Centre (BEQIC) with the automotive industry initiated the development of the SSFD to be used as a function analysis tool



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within an industrial engineering design environment in the automotive industry. As mentioned in Campean et al. (2010), the work of the BEQIC with the automotive industry was mainly associated with the deployment of a Failure Mode Avoidance (FMA) framework (Saxena et al., 2015) integrated with systems engineering design V-model (Forsberg and Mooz, 1998) to deal with failure modes early in the design process of automotive systems. Campean et al. (2011) discuss function analysis in the context of FMA is not integrated with the systems engineering requirements process. This prompted the introduction of the SSFD to support design FMA methodologies in industrial practice (Campean et al., 2011; Campean et al., 2013a). Figure 1 shows BEQIC FMA Framework where the SSFD is shown in a black rectangle with dotted line.

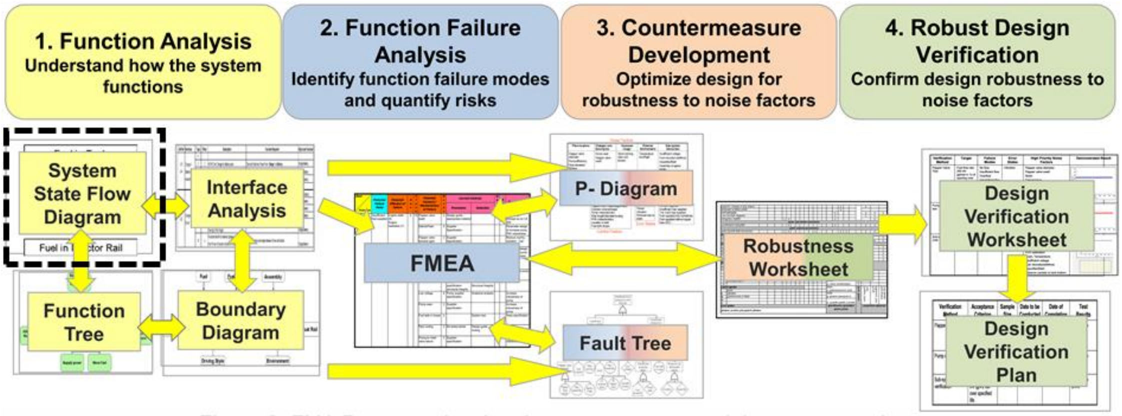


**Figure 1. BEQIC FMA process, showing the process steps and the support tools (Campean and Henshall, 2012)**

The SSFD methodology has been introduced as part of a learning intervention for a design methodology focused on robust engineering systems analysis and hundreds of engineers have been exposed to the methodology through its deployment in industry, including 2 major automotive OEMs, over the past 10 years (Henshall et al, 2017). The methodology has been applied to the function modelling and representation across a variety of disciplines (Campean et al., 2011; Campean et al., 2013b; Henshall et al., 2014; Naidu et al., 2017; Dobryden et al., 2017).

## 3. Methodology

The establishment of a rigorous reference framework for the SSFD function representation based on a critical review of the established function modeling frameworks and the introduction of a set of heuristics to guide the practitioner in its deployment by Yildirim et al. (2017) paved the way for the consistent deployment of the SSFD in industrial practice for the analysis of complex multidisciplinary systems. The research presented here aims to introduce a deep insight into the utilisation of the SSFD in industrial practice, gained through the analysis of technical reports in a major automotive OEM. The authors introduced the SSFD as part of a learning intervention for a methodology on engineering systems analysis in the context of FMA, i.e. Technical Accreditation Scheme Engineering System Analysis-FMA (TAS ESA-FMA) module. The engineers who have participated in the TAS ESA-FMA module were required by the Company to complete a workplace based project to apply the methodology in their respective areas to solve a current engineering problem or to improve current processes and practice. Each engineer had to submit a technical report in the length of 2000-5000 words on the timescale of the workplace project which was 6-8 months.

The first 100 engineering reports submitted between July 2017 and March 2020 based on the workplace based projects, after the launch of the TAS ESA-FMA module (January 2017), were selected for the analysis of the SSFD in the context of the implementation of the ESA-FMA methodology. These 100 reports were analysed at two stages. The first stage aims to offer a glimpse of the use of SSFD in these 100 reports with a focus on



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1. The usage of the SSFD across projects
2. Subsequent use of relevant FMA tools: Boundary Diagram, Interface Matrix, Interface Analysis Table and FMEA
3. Application level in the context of Systems Engineering V diagram: System, Subsystem and Component
4. The distribution of the usage of the SSFD across engineering areas of competence (CoC), e.g. Body Engineering

The second stage introduces a deeper analysis of a smaller sample of reports which were selected based on the quality of the SSFD application in teams involved in the development of a variety of systems. The first part of this analysis was quantitative and focused on

a) The usage of the SSFD across engineering disciplines
b) The integrity of the application at three levels: 1-Low, 2-Medium and 3-High. In line with the training provided by the authors to the engineers, the integrity of each application was evaluated based on the structure of the diagrams

The second part of the analysis is qualitative to a large extent and introduces a survey of the type of problems that people from industry encountered in the application of the SSFD which reflect the problems in practical function modelling. This part also focuses on the analysis of the strength (e.g. views considered useful and the specific advantages attained) and the impact of the SSFD pointed out by the reports.

As represented in the next section, two-staged analysis of these 100 reports allowed us to obtain insights into concrete experiences made with practically applying the SSFD in different disciplines and design contexts.

# 4. Results and Analysis

## 4.1. Distribution of Projects with SSFD across Areas of Engineering Competence

Figure 2 represents the overall usage of SSFD across the projects / technical reports, based on data collected from the individual review of 100 projects. As shown in Figure 2, nearly 3 out of 4 engineers (%72; 72 reports) used SSFD in their projects. This shows that they started the analysis of their systems by carrying out a system decomposition analysis on a functional basis.

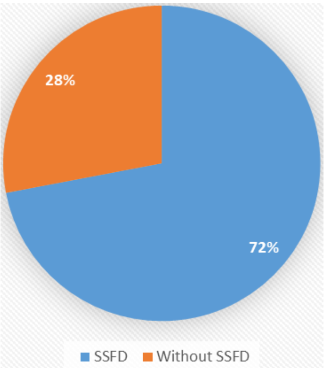


**Figure 2. Usage of SSFD across the projects**

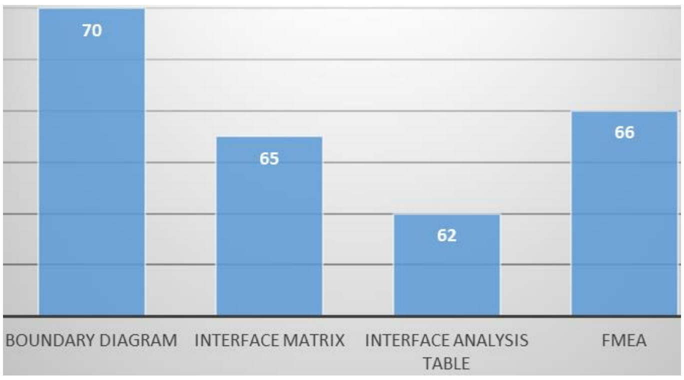


**Figure 3. Subsequent use of FMA tools**

Arrows in Figure 1 show the flow of information between the FMA tools. There is a direct information flow from the SSFD to Interface Analysis (Interface Matrix+Interface Analysis Table) and indirect information flow to Boundary Diagram and FMEA via Interface Analysis. Figure 3 represents the use of subsequent FMA tools in connection with the SSFD. Nearly all projects with the SSFD (70 reports) developed Boundary Diagram following the SSFD, while over %80 of 72 reports employed Interface Matrix (65 reports), Interface Analysis Table (62 reports) and FMEA (66 reports). In other words, over %80 of Interface Matrices, Interface Analysis Tables and FMEAs have carried out a SSFD function analysis. This shows that the ESA-FMA function analysis tools including the



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SSFD have been widely employed in the company, further substantiating the integration between the tools in terms of the consistency of the information flow between them and therefore shows a highly consistent application of the SSFD across the projects.
Figure 4 illustrates the analysis of the level of application for SSFD across the reports. This analysis shows that nearly 3 out of 4 projects focused on a subsystem level (%76), a component level (%73) and more than one level (%75), while 2 out of 3 projects (%66) approached the analysis on a system level.

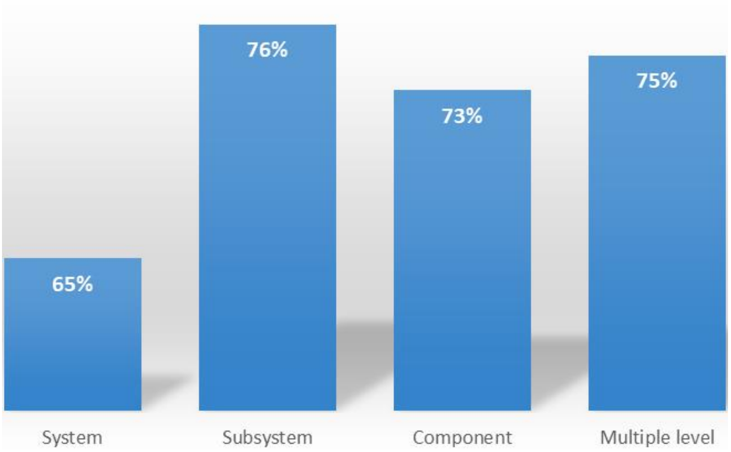


**Figure 4. Level of system analysis**

Figure 5 provides an analysis of the distribution of the number of SSFD applications with the phases of Product Development (PD), i.e. Service Operations, Assembly, PVT, System Integration, Product Creation and Concept (including advanced research). Figure 6 illustrates the distribution of the SSFDs with the centres of engineering competences in the company, i.e. Operations, Manufacturing, Engineering Laboratories, Electric Vehicles, Powertrain, Vehicle Engineering, Chassis Engineering and Body Engineering. Operations have the highest number of SSFD projects, this is followed by Manufacturing, Chassis Engineering and Electric Vehicles. The overall distribution of the SSFDs in the projects in Figure 5 and Figure 6 reflects the distribution of engineering workforce in the company.

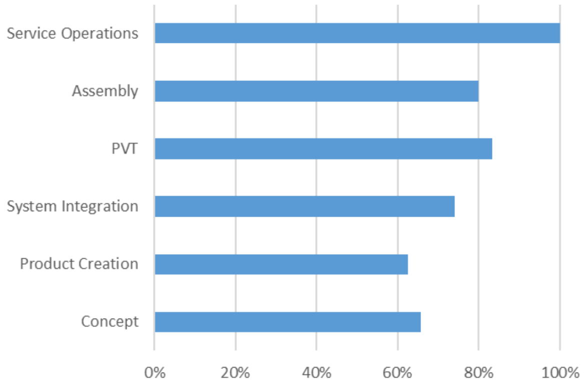


**Figure 5. Analysis of distribution of SSFD applications with phases of PD**

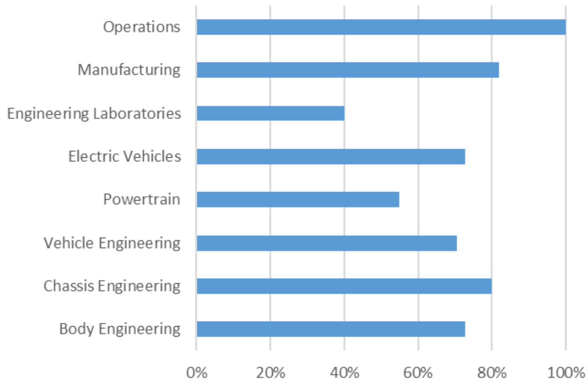


**Figure 6. Analysis of distribution of SSFD applications with engineering competence area**

## 4.2. Analysis of Usage of SSFD on Projects

41 out of 100 reports were selected for a detailed analysis of SSFD usage on projects. The selection of reports was based on two criteria: i) coherency of the SSFD application with the training material provided by the authors and ii) the overall marking of the report (this also reflects the quality of the application of other FMA tools in connection with the SSFD).



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Figure 7 represents the application of the SSFD across engineering disciplines: Mechanical, Mechatronics, Process, Service Development (SD), Control, and Electrical. Figure 7 shows that nearly 1 out of 2 reports (%44) focused on the analysis of mechanical systems, while 1 out of 5 reports (%20) used SSFD in the analysis of systems in Electrical domain. Similarly, nearly 1 out of 5 reports (%17) focused on the systems with control feature.
Figure 8 illustrates the level of integrity in the application of the SSFDs. The assessment of the integrity of the applications was carried out in line with the use of the guidelines provided to the engineers which are detailed in Yildirim et al. (2017). These are briefly the identification of i) main flow, ii) connecting flow, iii) branching flow and iv) conditional fork/join nodes as required. For example, linear diagrams including conversion operations were described as low-level integrity because the fulfillment of conversion operations requires the connection of the flows of additional resources to the main flow. Figure 8 shows that 1 out of 5 reports consists of diagrams with low-level integrity.

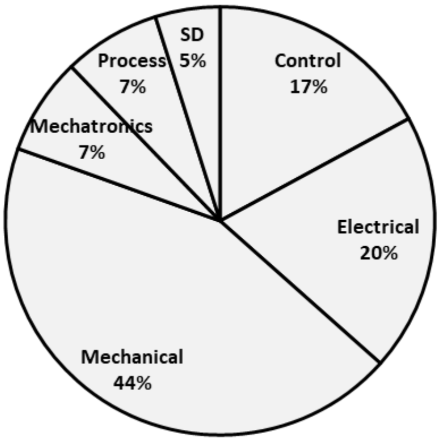


**Figure 7. Analysis of distribution of SSFD applications with engineering disciplines**

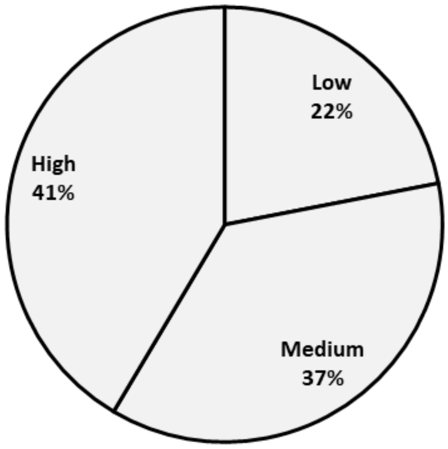


**Figure 8. Analysis of SSFD applications in terms of the integrity**

A detailed, individual review of the selected project technical reports was carried out to analyse the problems in functional modelling experienced by the practitioners during the project-based implementation of the SSFD. The top three problems pointed out by the engineers as per the reports (n) are:

1. The analysis and the representations of systems with **fork/join nodes** (n = 19);
2. The analysis and the representations of systems requiring **closed loops** (n = 9);
3. **Nested** function modelling of systems (n = 7).

The analysis of this smaller sample of reports shows that nearly %50 of engineers highlighted the item (1), while around %20 of them pointed out the items (2) and (3). A relatively small number of engineers expressed concerns in relation to the analysis of their systems with the SSFD:

- The difficulty in the identification of input-output of the system / black box (n = 3);
- Not being suitable in the analysis of static systems where there is no energy transfer or change in state is not noticeable (n = 2);
- Definition/cascade of system levels (n = 2);
- Translation of customer requirements for the vehicle level analysis (n = 1);
- The difficulty in understanding the state flow of systems where all flows are information, e.g. software (n = 1).

Some engineers clearly highlighted strengths of the SSFD and its impact in the system analysis:

- The flow of information to other FMA tools including FMEA and Interface Analysis Table (n = 14);
- Solution-neutral analysis of systems (n = 5);
- The integration with in-house developed tools (n = 4);


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- A smooth integration of a feature into a current system (n = 1);
- Providing an understanding of how a stakeholder goal is achieved (n = 1).

## 5. Discussion and Conclusions

This paper aimed to provide insights into the use of the System State Flow Diagram (SSFD), a function modelling method, in industry based on a large scale study with an automotive OEM. The methodology followed for the analysis of the use of the SSFD in the company provided a structured approach to the evaluation of the application of the SSFD within the company through the analysis of technical reports completed based on a workplace based project by engineers attending the ESA-FMA TAS module.

The analysis of 100 reports provided a good basis for assessing the reach of the methodology across the company, as well as the use of SSFD in term of the level of system analysis and in relation to other FMA function analysis tools. The limited uptake of function modelling in practice has been discussed by many scholars. The quantitative analysis in Section 4.1 showed that the SSFD was picked up by the majority of engineers who worked at various phases of Product Development (PD) process and engineering competence areas. This is a useful indicator of the propagation of the SSFD, as a function modelling framework, within the organisation. This is reflected by a good distribution of projects across all areas of engineering competence and phases of PD, shown in Figure 5 and Figure 6, which is coherent with the workforce of the company.

Distribution of subsequent use of the key methods (Boundary Diagram, Interface Matrix, Interface Analysis and FMEA) in connection with the SSFD in Figure 3 and level of system analysis in Figure 4 suggests that there is a consistency in the application of the SSFD in the context of the ESA-FMA TAS module across projects in all engineering areas and PD phases. This also highlights different uses of the SSFD such as being used as a basis to model potential failure events. 75% of the projects have carried out the SSFD at multiple system levels, which shows the integration of the SSFD methodology with the systems engineering approach.

The fact of reaching all areas of engineering competence and phases of PD is important as an indication of the great potential of the SSFD to support cross-disciplinary collaboration and comprehension. This is an important factor for improved team communication (such as fostering a shared understanding), which is essential in a reduction in development time and design errors.

A detailed analysis of a small sample of reports in Section 4.2 provided a good picture of the quality of SSFD applications and the distribution to engineering disciplines. This section also represents the strength of the SSFD in function modelling as well as problems and concerns about its use in function modelling stated by the engineers, and also observed by the authors in the use of established function modeling frameworks. For the sake of maintaining the objectivity and the integrity of the analysis, only those strengths and problems stated clearly by the engineer in the report and validated by the application were included in the analysis.

The quantitative analysis provided in Figure 8 shows that a significant number of projects includes a SSFD application with a good level of integrity. Figure 7 is largely associated with inter-disciplinary projects highlighted in Section 4.1, where the application of the SSFD has facilitated more effective teamwork.

The detailed analysis of the reports also revealed various problems in functional modelling experienced by the engineers. These problems can be attributed to both academic and industrial needs. The top three issues were described associated with the need for i) fork/join nodes, ii) closed loops, and iii) nested function analysis of systems:

- The application experience of the SSFD methodology in the company made clear the need for the enhancement of the methodology to boost its impact in academia and industry. Drawing on this experience and data obtained from the reports, Yildirim et al. (2017) have improved the SSFD methodology based on its critical review against the established function modeling frameworks to boost its broader academic and practical impact, addressed (i), as well as some other concerns highlighted by the engineers including the identification of input-output of a system and understanding the state flow of systems.



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- Campean et al. (2018) focused on (iii) by introducing the use of the SSFD on a systematic modelling of functions through nested systems. Similar to Yildirim et al. (2017), this work also focused on addressing some other problems pointed out by the engineers, in particular cascade of system levels.
- In terms of (ii), we acknowledge the concerns of the engineers. Most of current function modelling approaches, including the SSFD in this case, pertain to the analysis of open loop systems with very few control functions. However, in particular with the development of autonomous systems, the importance of feedback control systems has increased dramatically. Further work is required on the application of the SSFD to closed loop control systems. This will also provide further verification on the applicability of SSFD for the modelling of information/date flows. It is relatively easy to model the main flows of material and energy through systems even with the established functional modelling approaches. However, this is not straightforward in the case of the flow of information/data set, i.e. it is not always easy to conceptualise this type of flows (e.g. a signal can possess 8 bits data) in the concept phase.

Being linked to the established technically oriented methodologies (such as FMEA), the SSFD provides practitioners with a better understanding of how failures are initiated in system of interest (e.g. identifying potential failure paths and prioritize the problems in a more structured way). Software/control systems often use AUTOSAR layered architecture. Our future work will also focus on validation of SSFD with software-architecture driven standards (such as AUTOSAR) to assess its usability and applicability for the design of automotive electronic control units. As an example, practitioners often use "state flow" modelling tool (developed by Mathworks) to design control logic of electronic control units but this does not offer descriptive functions capability around modelling states which SSFD can complement.

Two main conclusions from this evaluation of the use of the SSFD in the context of the ESA-FMA TAS module based on the analysis of 100 technical reports and a more detailed analysis of a small sample of reports on projects can be summarised as follows:

1. The quantitative assessment has shown engagement of engineers with the SSFD from across all i) engineering competence areas, ii) phases of PD phases, and iii) levels of systems;
2. There is evidence of consistent usage of the key tools (such as FMEA) in connection with the SSFD across the PD organisation. This increases the integrity of the analysis in the identification of new functions, new requirements, new failure modes and therefore new test cases. In other words, the integration of with the key FMA tools (as well as the integration with in-house developed tools as noted by some engineers) led to better outcomes for those projects.

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