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WP1/D1.5: Study Results

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1 Introduction

This document summarizes the results of the performed Systems Engineering study. This section documents the study's goals, scope, and participants from selected domains as well as the general process followed for conducting the study. The second section presents the analysis results based on minutes taken during the interviews performed. The third section summarizes the key outcomes of the study and the fourth section concludes with overall recommendations for companies and fields of action.

1.1 Goal and Plan

The goal of the study is to collect the state of the practice regarding Systems Engineering in Germany and Europe, focusing on challenges and solution approaches in terms of best practices (work processes, methods, and tools).

The primary plan for obtaining best practices was to use a series of interviews. If necessary, i.e., if too few interviewees were to be found, the secondary plan was to retrieve the required information in survey style (e.g., as part of an industrial conference).

1.2 Scope

The scope of the study can be summarized along the following dimensions:

1. The study will focus on Systems Engineering best practices across different domains and will not be specialized to any single domain.

2. The product of the participating companies must have software and hardware parts; that is, a company doing Systems Engineering to produce solely hardware components is not in the scope.

3. The study will focus on aspects related to the interfaces and the integration between Software and Systems Engineering (e.g., how to translate system requirements into software requirements), as we want to understand the motivation and the drivers for companies to move from separated disciplines to an integrated Systems Engineering approach.

4. Regarding the Systems Engineering processes (as based on ISO/IEC 15288 and ISO/IEC 12207), we will focus on the Technical Processes as well as on the Software Implementation, Software Support, and Software Reuse Processes as the top priority regarding best practice collection. Other process

areas, such as Contracting, Project, or Project-Enabling Processes will be of secondary priority, with one exception: processes related to skill/competence development for human resources and knowledge-management-related activities.

5. Regarding technical processes, the study will try to address different aspects from the whole V-model (e.g., requirements, design, coding, testing, etc.). However, should the discussions get too broad during an interview, the focus will be on practices regarding requirements engineering and quality assurance.

6. The study will include organizations/units classified as small and medium-size enterprises (SMEs) as well as large organizations (LOs). However, as more mature Systems Engineering practices are assumed to be available for LOs, the majority of companies will stem from that area.

7. The major criteria for selecting organizations/units will be their maturity and competencies regarding Systems Engineering. Other aspects, such as having a global/international business, will be secondary.

8. Regarding the dependency of companies, there will be no special focus. Companies from the supply chain in a given domain may participate just like manufacturers or system integrators.

9. The focus of the study will be on companies from the areas of Automotive (Transportation), Production, Health Care, and Aerospace. The number of companies will vary across these domains depending on available contacts.

1.3 Participants

Overall, 42 invitations were sent to people from 34 different organizations. 22 of them agreed to be interviewed. Finally, 20 interviews with people from 18 different companies were performed.

The following companies agreed to be mentioned as a study participant:

Company	**Domains**	**Type**[1]
Airbus DS Electronics and Border Security	Aerospace, electronics	LO
Art of Technology AG	Production, healthcare, aerospace	SME
AVL LIST GmbH	Automotive	LO
Binder Elektronik GmbH	Industry electronics, healthcare	SME

[1] SME = Small or Medium-sized Enterprise, LO = Large Organization

Company	Domains	Type[1]
Airbus DS Electronics and Border Security	Aerospace, electronics	LO
camLine GmbH	Software supplier for production, healthcare, automotive, aerospace, and semiconductors	SME
CIBEK technology + trading GmbH	Solutions for senior citizens, automation technology	SME
ETAS GmbH	Automotive	LO
Hella KGaA Hueck & Co.	Automotive, Electronics, Lighting	LO
Robert Bosch GmbH	Production, automotive, consumer electronics	LO
ZF TRW Automotive Holdings Corp.	Automotive	LO

1.4 Process

The following process was followed to contact the participants, organize an interview timeslot, and document and analyze the results.

1.4.1 Contacting Phase

As there were multiple contact persons for each organization/unit, the contacting procedure was initiated in several waves. First, the preferred contact person for an organization was contacted via email/telephone. If the person was not available or did not consider him-/herself suited, but mentioned a person with more appropriate availability/suitability, this replacement person was contacted. If no alternative person was mentioned, we took the next person from that company from our list if there was someone left.

The invitation for participation was sent by the internal contact provider at Fraunhofer IESE, who (ideally) personally knew the contact person. If a person did not respond within a couple of business days, a reminder was sent. If a person did not respond within a couple of weeks, an alternative person was contacted.

If a contact person agreed to be interviewed, an appointment was made and the person became the interviewee. The appointments themselves were organized centrally. The contact person's preferred time slot was determined. Afterwards, the coordinating person appointed two Fraunhofer IESE researchers from the project team as moderator and recorder, respectively, of the interview.

1.4.2 Execution Phase

In preparation for an interview appointment, the moderator sent the list of questions to the interviewee (typically one week before the interview started). The moderator was available for questions regarding the interview series in general. All interviews were conducted using a telephone/video conferencing system. The moderator read out and explained the interview questions. If the interviewee was not able to answer the question, the moderator offered some example answers to demonstrate the general direction while making clear that the specific problems of the organization/unit of the interviewee might be different ones. The recorder wrote down the keywords of the answers in order to summarize the outcomes in the minutes later on. The interview was not recorded literally.

After the end of the interview, the recorder stated a date by which the minutes were to be sent to the interviewee, when the study results were planned to be available, and agreed with the interviewee on a date by which the answers could be authorized by the interviewee.

The interview minutes were structured according to the interview questions and parts. It was indicated in the minutes which information can be used in the final interview series report as is and which information would have to be anonymized and not shared with third parties.

After that, an anonymized version of the minutes was created to be provided to the sponsor of the study. The minutes of all conducted interviews and their state were documented.

1.4.3 Analysis Phase

During the interview, minutes were taken by a second person. They were then anonymized prior to the analysis of the interviews.

Our procedure for the analysis of the expert interviews lies between meaning condensation and meaning categorization, but also follows the latest approach of using common sense in combination with quantitative and textual methods. Our approach to condensing and categorizing meaning was inspired by the grounded theory approach developed by Strauss and Corbin [SC98]. That is, we took the data from the first interview and identified initial categories. In most cases, this was done by replacing uncommon wording with more common wording. Then we incorporated the data gained from the next interview in the following way: If the data was considered to be already reflected in some existing category, the inherent counter for this information was incremented; that is, the category was more evident. In case the data was not yet reflected, a new category was added. According to grounded theory, this procedure has to be performed until some new knowledge is obtained. In grounded theory, each step has to be recorded by means of memos and diagrams.

For analysis purposes, a workbook was created containing one separate spreadsheet for all answers given to each of a total of 29 questions. In addition, one spreadsheet was created containing general characteristics of the interviewee's organization/unit. The analysis of the answers given to the 29 questions plus the characterization sheet was split among four Fraunhofer IESE researchers.

Each researcher analyzed the answers to his/her assigned questions independent of the others. At regular time intervals, the researchers met to discuss the analysis results as well as cross-cutting topics, especially related to possibly contradictory information.

Finally, all analysis results were summarized across all answers to the questions in a list of core outcomes of the performed study.

1.5 Discussion of Potential Threats and Limitations

This section discusses some of the potential threats and limitations (based on [USC16]) of the performed study related to the methodology applied and their performers:

(1) Sample size: The overall number of interviews performed is fairly small. This limits the generalizability of the results on the one hand, but also our possibilities of analyzing relationships among the answers on the other hand. Taking into account the limited time available for conducting the study and the intensity and duration of a single interview, it was difficult to encourage more people to participate and get a reasonable amount of interview data that could be analyzed feasibly within the available time span. Overall, 42 invitations were sent. Of these, 22 accepted to be interviewed, and 20 interviews were finally conducted. The benefit of this relatively small number of interviews was that it was possible to focus more on the single answers provided and to get deeper insights into single cases.

(2) Scope: The basic aim of the study was to gain insights into challenges and solution approaches for Systems Engineering. This aim would be mapped to a relatively large number of companies. Therefore, we carefully restricted the scope for participation as defined in the section above. Furthermore, the invitations for interviews were limited to people known from previous projects and collaboration. This guaranteed a good fit to the defined scope (as the main characteristics of the companies for which these people work are mainly known) and general openness to participate in the study. However, because of that selection mechanism, the final sample is fairly small and generalizability is limited.

(3) Prior research: Before conducting the study, we analyzed existing related work fitting the general goals of the research. Even though there is a certain overlap between the questions asked in previously conducted studies and in the current study at hand (e.g., in terms of challenges), the defined scope and intention are different. The current study focuses on a pure industrial setting and aims at analyzing challenges as well as established and future practices for overcoming them across different domains and company sizes.

(4) Questionnaire: The questionnaire used to guide the interviews was systematically derived from the goals of the study and peer-reviewed internally by Fraunhofer IESE researchers. After that review, we decided to split some questions, as two or more aspects were mixed in one single question (such as asking for current and future trends). Also, some questions were skipped during the construction of the questionnaire in order to reduce the time required for a single interview. The decision to skip a question was made based on its importance for the research goals. Initially, all questions were open without any answers provided.

During the first two interviews, it was experienced that some questions were hard to answer without some further hints about the intention of the question. Furthermore, the interviews took longer than initially planned (60 minutes at most). For that reason, example answers (mostly containing potential alternatives) for 13 out of the 29 questions were provided. The example answers were created based on the related studies previously analyzed and on the experience of the Fraunhofer IESE researchers from past Systems Engineering projects. The examples had been constructed prior to the first interview, but only as part of the internal guidelines for the conductor of the interview. In later interviews, the example answers were sent to the interviewee beforehand to provide better orientation. However, it was made clear that the interviewee should not just select from the provided examples, but should also be encouraged to think beyond them. The consequence was that coding of the provided answers was simplified as many answers could be mapped to the existing list. This contributed to facilitate comparability of the answers. Furthermore, the time for conducting an interview could be significantly reduced.

(5) Self-reported data: The participants of the study were asked to report about their specific knowledge and about experience limited to their specific context in the organization/unit. They were asked to explicitly answer based on their first-hand experiences and not to make assumptions about what is going on outside their responsibilities and fields of expertise. However, the answers given are still biased by their personal perception. As only one person of an organization or of a specific unit of a (larger) organization was interviewed, there was no chance to analyze discrepancies among answers; the researcher had to trust what was said about the organization/unit. The only possibility was to check whether there

were contradicting opinions within a certain domain. But even this was limited because of the small sample size.

(6) Convenient sample: How representative are the contacts of Fraunhofer IESE regarding the target population and defined scope? As a German applied research institute, Fraunhofer IESE has participated in numerous research and development projects in the area of Systems Engineering in the last 20 years. From that network, a relatively large number of contacts existed, who were invited to participate in the study.

(7) Trust and openness: The Fraunhofer-Gesellschaft is well known in Germany as an objective, neutral, and independent partner. This guarantees a certain openness towards participating in a study as well as openly talking about challenges and solution approaches (at least if there is no conflict with the core intellectual property of the company). Furthermore, it was made clear in the invitation to the interview for what purpose the results would be used, that the minutes would be anonymized before being analyzed, and that the interviewees would have the chance to review the minutes and would have to explicitly approve the use of the minutes as part of the analysis.

(8) Schedule: The schedule for performing and analyzing the interviews was quite tight. The interviews had to be performed between June and August 2016 during the typical German summer vacation time, meaning that people are often only available for a limited amount of time. Furthermore, the analysis results were due in the middle of September in an initial version, shortly after completion of the final interview. The first issue was addressed by inviting people to participate to whom some kind of relationship existed from previous projects. The second issue was taken care of by performing an iterative analysis approach and incrementally adding new evidence from new interviews.

(9) Language: All interviews were performed in German and then translated into English for further analysis. There is a risk that some terms may have been translated inaccurately. This might have happened especially because the researchers performing and documenting the interviews have different backgrounds than the interviewees and, furthermore, because some company-specific terms were used. The first interview minutes were documented in German and sent to the participants for approval. The translation was performed afterwards. Because of the translation issue, it was decided later on to send the minutes in English right away. This gave the interviewees the chance to check the accuracy of the translation to their best knowledge and was done to confirm that the interview minutes reflect the opinion of the interviewees properly. Furthermore, the interviewees had the chance to make extensions and corrections to the given answers.

(10) Validity of analysis: The 29 questions were split among four researchers of Fraunhofer IESE to be analyzed in terms of communalities and differences among the answers provided. Each of these researchers performed the coding of answers and the analysis independent from the others. Although no peer review of the results was performed, a series of group meetings was organized to present and discuss the individual coding and analysis outcomes. Furthermore, the researchers tried to discuss aspects across question groups such as contradictory or supporting statements. However, the statements given were largely consistent with each other and no real contradictions were observed during the analysis process. Finally, the four researchers documented the interpretation of their analysis results as part of this report. All analysis results were then reviewed by all four researchers.

2 Analysis Results

This section contains the analysis of the answers provided to the 29 questions (12 heading questions with sub-questions) asked. The questions were grouped into four different interview parts dealing with the context of the participant and her/his organization/unit, the challenges related to Systems Engineering they confronted, solution approaches and practices for addressing the challenges, and an outlook to the future improvement potential of Systems Engineering and the organizational capabilities in general.

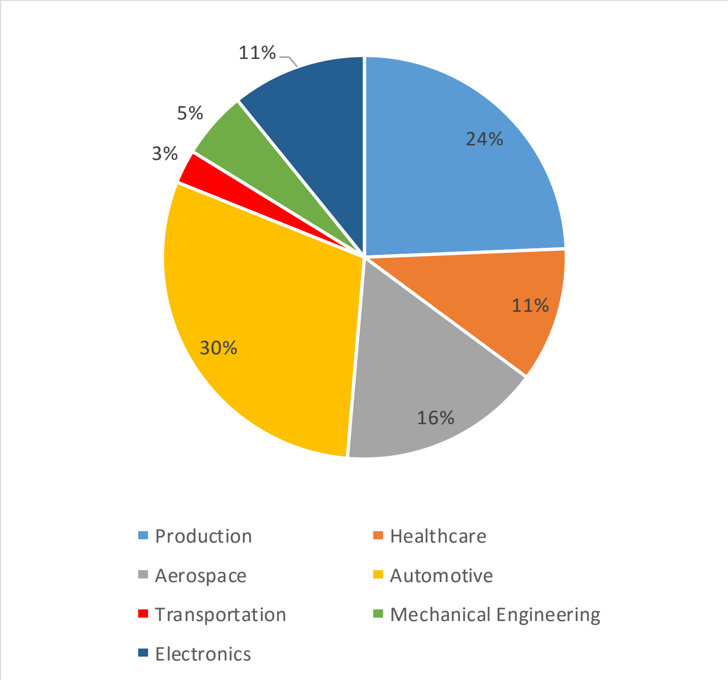

Figure 1: Distribution of participants across domains

Overall, 42 invitations were sent to people from 34 different organizations. 22 of them agreed to be interviewed. Finally, 20 interviews with people from 18 different companies were performed. Among the 20 interviews performed, there were 6 organizations classified as SMEs and 14 large organizations. The distribution of domains can be seen in Figure 1. The majority of companies are from the automotive and production domain, followed by aerospace, transportation, and healthcare. A few companies are from the electronics and mechanical engineering domain.

In the following, the questions for each interview part are listed in the way they were posed to the participants of the study. For each question, the analysis of the answers is presented below the question text.

2.1 Part 1: Context

Q1: Could you tell us about your organizational role and which part of the organization (unit) you represent?

The interviewees were divided into three groups according to their role in the organization: Higher Management (CEO, COO, Directors), Engineers (Systems Engineer, System Architect, Engineer, Requirements Engineer, etc.), and Middle Management (Program Manager, Project Manager, Quality Manager, etc.).

Overall, 20 participants took part in the interviews. Four of them were Senior Staff, 8 were Engineers and 8 have a Middle Management role.

Twelve participants represented the development part of their organizations, three belonged to management, and three participants were from the research unit. Two participants filled roles spanning several units.

Q2: What kinds of products does your organization/unit produce and what are general trends your organization/unit is currently confronted with that will change the products/the product engineering fundamentally in the future (5 years from now on)?

Companies produce various types of products, including software (44% of participants), hardware or machines (35% of respondents), electronics (21%) (multiple answers could be given to this questions as some companies produce multiple producs of different types).

The companies are currently confronted by many trends in product engineering. Some of them are common, such as increasing requirements complexity (60% of the answers), shorter time to market/shorter R&D phases (55%), and increasing product variation due to customer expectations for individualized products (50% of the respondents). 45% of the respondents mentioned increasing cost pressure and global product engineering as recent trends. A list of the most popular trends is presented in Figure 2.

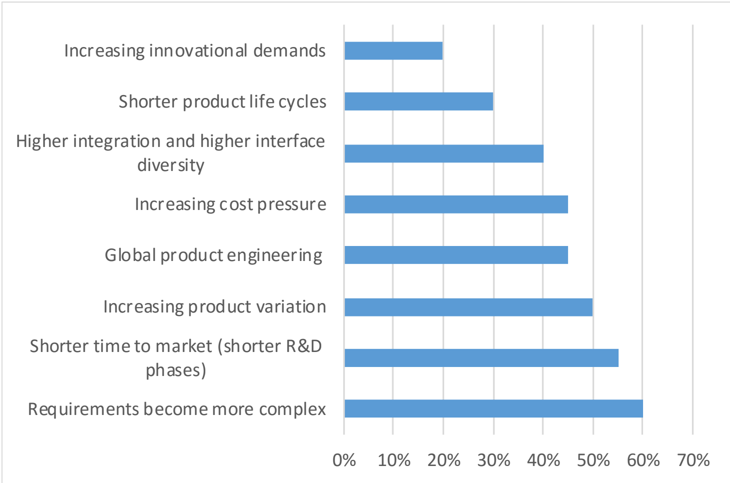

Figure 2: Recent trends

Many respondents assume that the current trends will remain relevant over the next five years, but according to the respondents, the leading trends in the future will be the growing multi-disciplinary development, increasing cost pressure, and shorter time to market (each of them was mentioned in 20% of the cases) (see Figure 3).

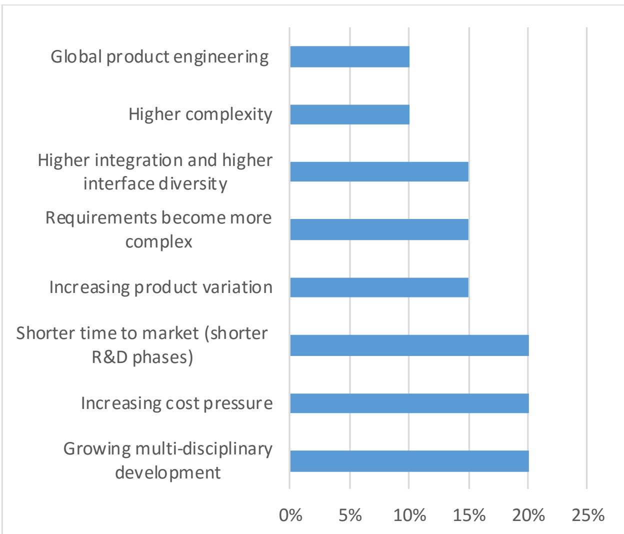

Figure 3: Trends in 5 years

2.2 Part 2: Challenges

Q3: What role does software play in your product?

85% of the answers rated the role of software "very important, important, or even essential"; 10% gave no answer; 5% could not provide a general answer to this question because the importance differed from product to product (Figure 4).

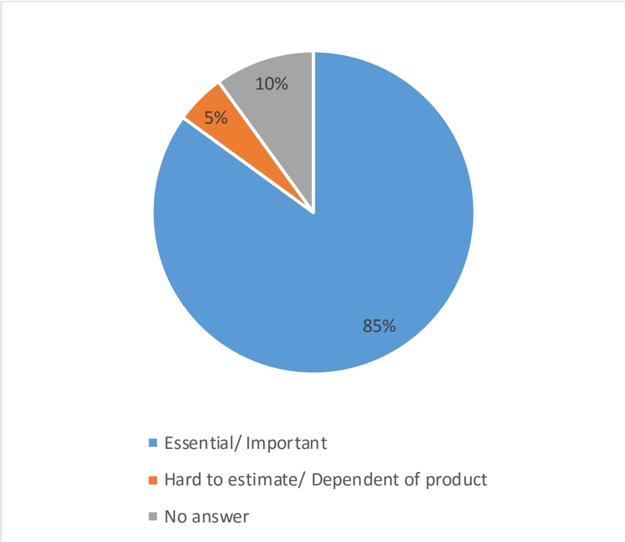

Figure 4: The role of software in the products

Q3.1: How big (roughly) is the typical proportion of software/software engineering in the overall budget today?

35% of the respondents estimated the software/software engineering budget to be up to 50% of the overall budget, while 35% estimated it as being up to 70%. 15% of the companies plan up to 90% of their budget for software/software engineering (Figure 5). Some interviewees were not in the position to estimate the proportion of software/software engineering in the overall budget (5% of the answers).

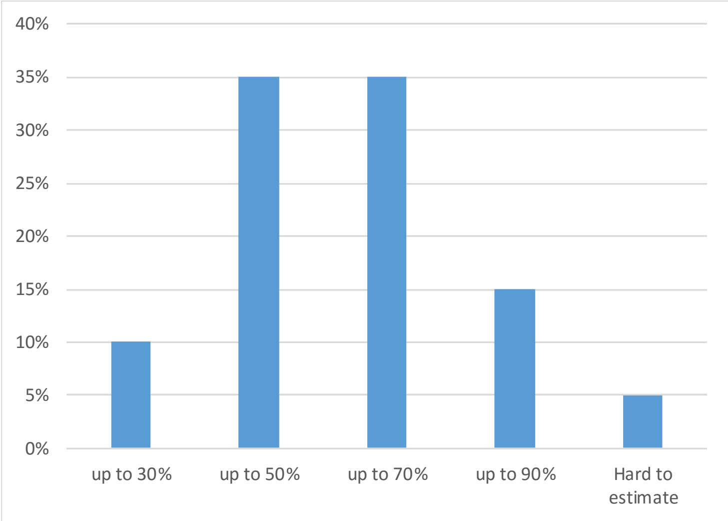

Figure 5: Proportion of Software/Software Engineering in the overall budget

Q3.2: How big will it be 5 years from now on, taking into account the trends you have stated?

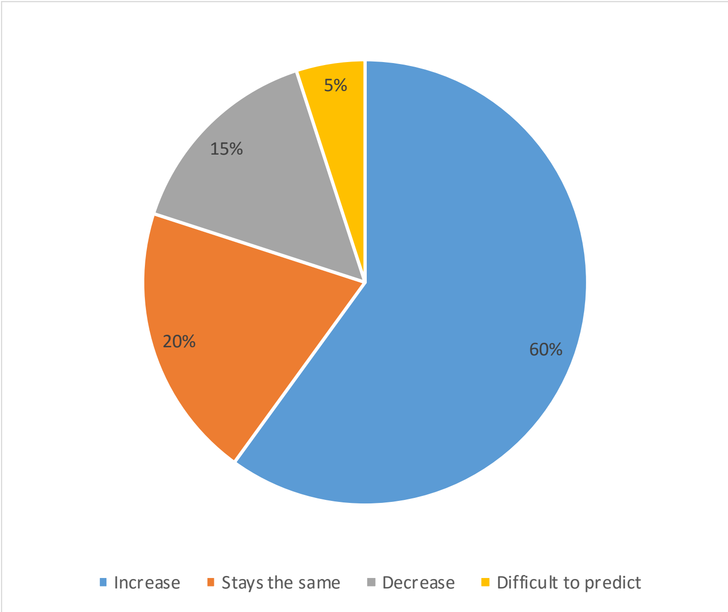

Figure 6: Proportion of Software/Software Engineering in 5 years

Even though 60% of the respondents predicted an increase in expenditures for software engineering in the near future, 15% said that they are trying to reduce that figure. Among the reasons given for these reduction efforts were better quality engineering, lower number of developers, company plans to focus more on product development instead of individually tailored projects, and more configuration of software instead of coding. 20% expect no change; for 5% it was difficult to predict an answer (Figure 6).

Q3.3: If there is an increase, where does the increase come from? Will that also yield a change in terms of the organization?

One can see in Figure 7 that 15% of the respondents said that the percentage of the budget for software/software engineering will grow due to an increase in the development of standardized software architectures (15%) and an increase in software development for the level of functionality required in the future (15%). It is also expected that networking/connectivity of devices will increase significantly (15%). 10% mentioned that they expect changes in terms of organization, such as growth in the different units of the organization, domain-related re-organization. Intelligent cloud (Cloud Computing, Big Data) and increasing virtualization of testing and simulation in general play an important role, too (10% each).

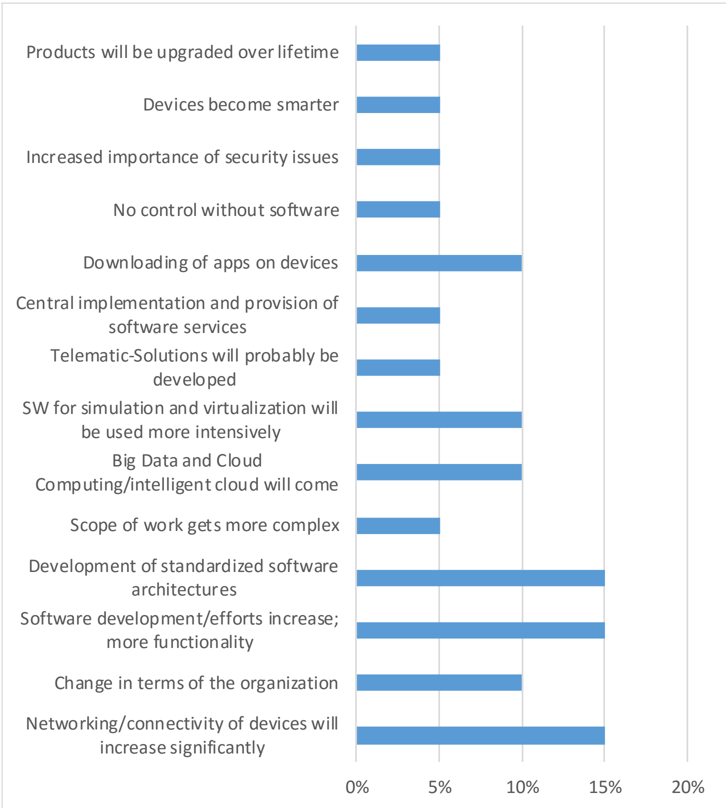

Figure 7: Proportion of reasons for Software/Software Engineering budget increase

Q4: How important is Systems Engineering?

Q4.1: Does your organization/unit historically come from a Software or Hardware Engineering-driven process?

The vast majority of all organizations (approx. 85%) have their origin in hardware development or in both hardware and software development, and have transformed in the last few years from a Hardware-Engineering-driven process to a Systems-Engineering-driven process (cf. Figure 8). This is especially the case for the large organizations, which all have their origin in hardware development. Only 30% of the small or medium-sized organizations have their origin in pure hardware development. 15% of all organizations have a background of both hardware and software development.

About 15% of all the organizations have been producing software since their beginning. These organizations do, of course, still apply Software Engineering methods. Nevertheless, they have also transformed from only Software-Engineering-driven processes towards Systems-Engineering-driven processes because customers demand more complete solutions instead of isolated software systems.

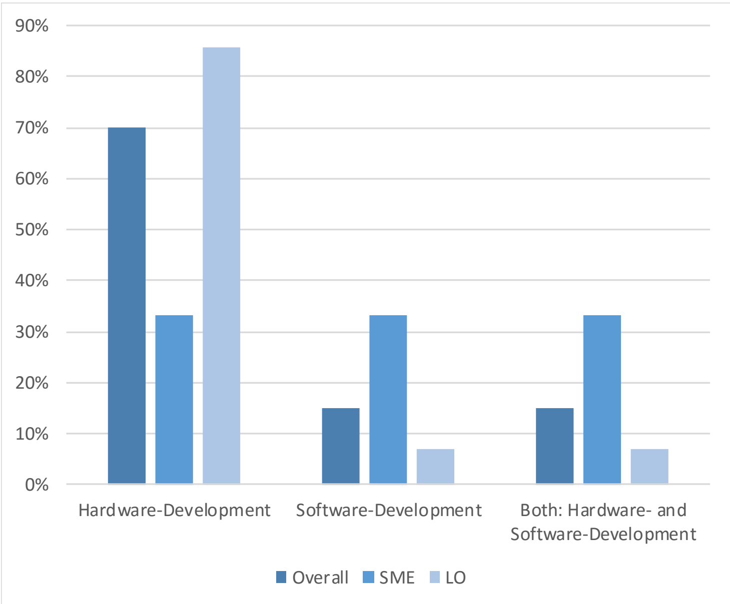

Figure 8: Where do the organizations come from?

Q4.2: What is/was the trigger for your organization/unit to transform from your previous engineering process to Systems Engineering?

There are a lot of different individual triggers that make organizations switch from their traditional development process to a Systems-Engineering-driven process (cf. Figure 9).

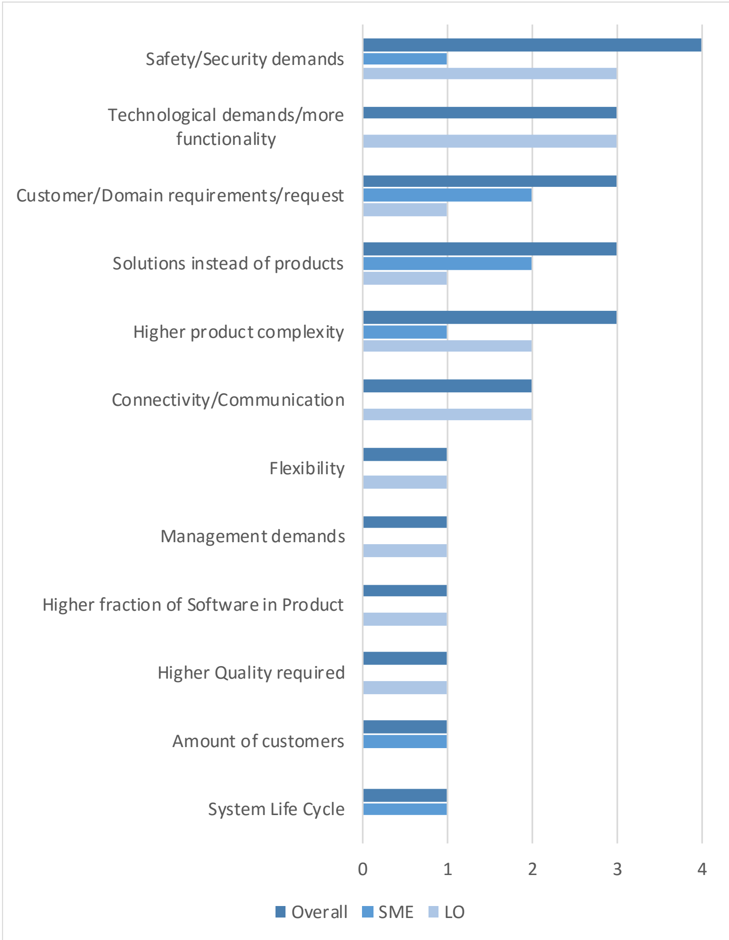

Figure 9: Triggers for transforming to Systems Engineering

Some of the commonly mentioned triggers include fulfilling safety/security requirements (e.g., registration of products before they are allowed to be sold), increasing product complexity (e.g., customer demand for more functionality), the need to provide full solutions consisting of hardware, software, and services instead of a small hardware or software product only, or higher interconnectivity and networking of products (e.g., networked operation or cloud services).

A few organizations are trying to transform from the production of individual customer-specific products towards the creation of products/solutions for the mass market that do not have to be individually tailored to a customer but instead can be configured flexibly. These organizations argued that this transformation process can only be mastered with a Systems Engineering approach.

In the automotive application domain, the same triggers can be observed when we look back at the transformation from mechanical engineering via hardware/electronic engineering with analog control systems to systems that are totally controlled by software, which took place beginning in the 1990s. This was the time when the first Systems Engineering processes were introduced among automotive manufacturers.

Finally, it can be observed that most organizations transformed their engineering process into a Systems-Engineering-driven process within the last six years (timespan 2010 – 2015).

Q4.3: How important is Systems Engineering in general (including project processes, technical processes, agreement processes, and organizational processes) from your perspective today (on a scale from 1=not important to 10=essential for survival)?

All organizations state that their implemented Systems Engineering process is important, very important, or essential (cf. Figure 10). The lowest importance value given by the participating organizations is 5 (moderate importance), the highest value is 10 (essential for survival). The average importance is 7.6, meaning important.

For about 25% of the participating organizations, this process is really essential (importance value 9 or 10). About 35% of all participating organizations stated that Systems Engineering is only of moderate importance (importance value 5 or 6). All other participating organizations gave values in between. The standard deviation is 1.5, meaning that the answers given are within a narrow margin.

There is no organization where Systems Engineering does not play any role or just a minor role. No significant difference between large organizations and SMEs can be discovered.

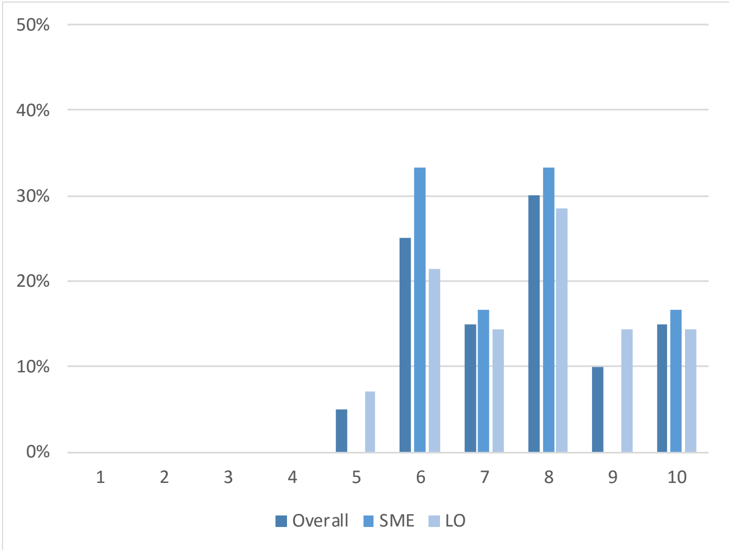

Figure 10: The importance of Systems Engineering today

Q4.4: How important will it be in 5 years for your organization/unit taking into account the trends you have stated?

Nearly all organizations estimate that Systems Engineering will become more important in the future. The average importance is increasing significantly from 7.6 to 8.7 within the next 5 years (cf. the upwards shift of the importance values from Figure 10 to Figure 11). This increase is seen in general across all types and sizes of organizations and also across all application domains. Nevertheless, it can be seen in Figure 11 that large organizations generally estimate a higher importance value in 5 years compared to SMEs. This can be interpreted such that Systems Engineering will play a more important role in large organizations in the future than in SMEs.

The standard deviation decreases from 1.5 to 1.1, which means that the estimated importance in 5 years is even more focused around the average importance of 8.7 (more organizations estimate the same higher importance).

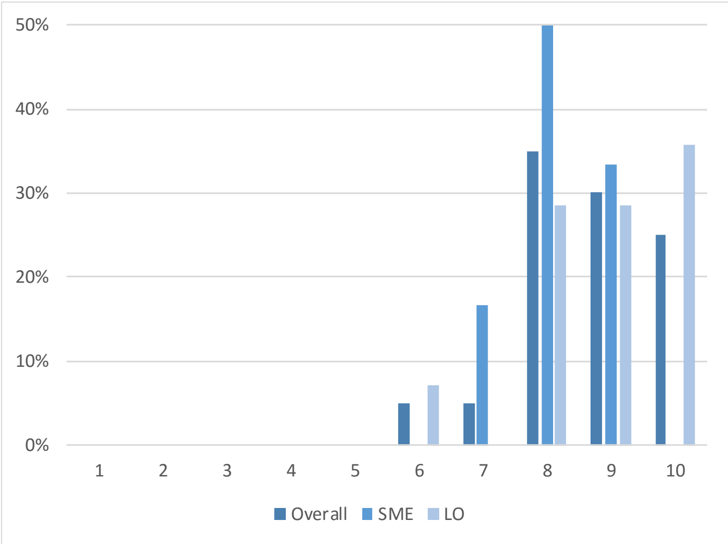

Figure 11: The importance of Systems Engineering in 5 years

Q4.5: What makes it so important?

Most participants stated that the reasons for the importance of Systems Engineering processes and methods are customer demands for higher product quality and the concurrent increase in product complexity, especially regarding platform/integration requirements (cf. Figure 12).

For SMEs, the main reasons are domain demands, customer/supplier demands, keeping/increasing product quality, and efficiency/cost reduction, which require Systems Engineering approaches.

For large organizations, the main reasons are managing the complexity of products and integrating components/platform requirements, which require Systems Engineering approaches.

Some organizations plan to address the medical application domain in the near future. This will result in higher regulation and registration requirements in this domain (domain demands) in combination with the need to certify specific development and documentation processes. These organizations plan to further develop their Systems Engineering processes to cope with these new challenges.

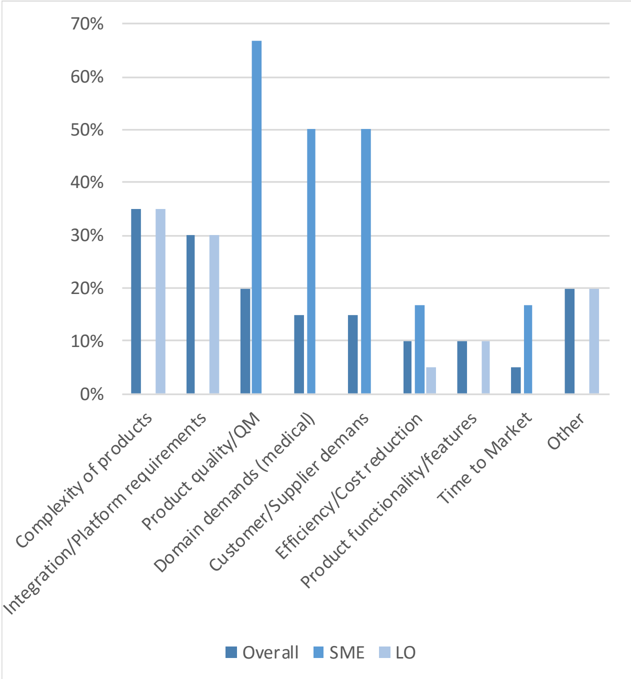

Figure 12: Why is Systems Engineering so important?

Q4.6: If there is a change in the importance, where does this change come from? Why is Systems Engineering becoming more important?

Similar to Q4.2 (triggers for transforming to a Systems-Engineering-driven development process), the reasons for the increased importance of Systems Engineering in the next 5 years are highly diversified (cf. Figure 13).

In alignment with Q4.5 (importance of Systems Engineering), about 35% of the participants stated that the main reason for the increased importance of Systems Engineering is their product development roadmap with future or further developed products/solutions becoming more complex (containing more functionality, containing new technological features).

For SMEs, the main reasons for the increase are customer or supplier demands, ensuring product quality, and handling the complexity of the products.

For large organizations, the main reasons for the increase are handling of product complexity, integration of new functionality and technological features, integration of product components with platforms and corresponding communications features, and safety/security aspects.

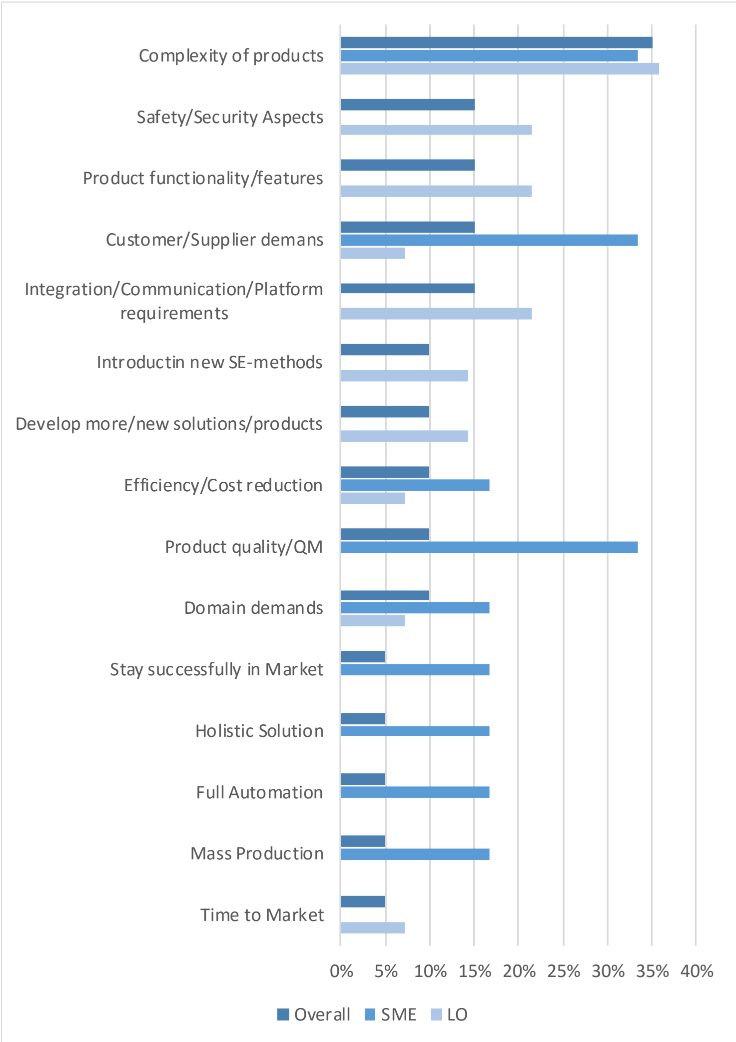

Figure 13: Reasons for the change of importance

Q5: If we talk about System Engineering, what are the challenges your organization/unit is currently confronted with (e.g., with regard to your products, system development processes, organizational structures, required competencies)?

Change management within the organization is the top challenge that nearly all organizations are currently confronted with, followed by requirements and interface management (cf. Figure 14). Other important challenges are modeling and simulation, data and information management, ensuring product quality, establishing/keeping methodological skills within specialist disciplines and across disciplines, establishing coherent tool chains, and human resources management.

SMEs are mainly confronted with change management within the organization, methodological skills within specialist disciplines and across disciplines, establishing coherent tool chains within the organization and across organizational boundaries, and ensuring product quality (e.g., reliability, safety, security).

Large organizations are mainly confronted with requirements and interface management of complex systems or even systems of systems, modeling and simulation, change management within the organization creating acceptance of new approaches and technologies, establishing coherent tool chains within the organization and across organizational boundaries, and ensuring product quality (e.g., reliability, safety, security).

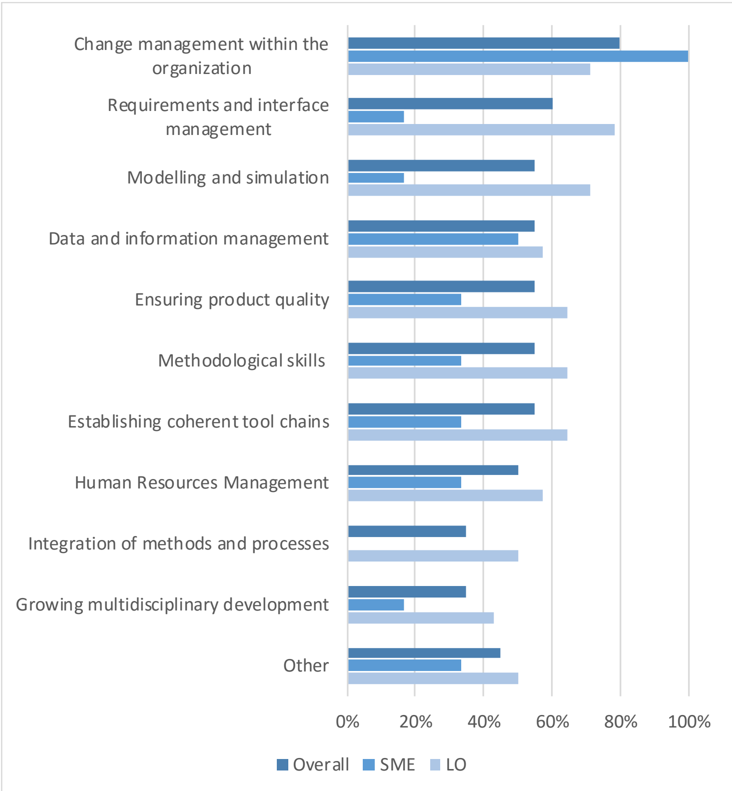

Figure 14: Current Systems Engineering challenges

Additionally, nearly every organization is fighting other individual challenges depending on its current product roadmap, process organization, infrastructure, or tool chain. In Figure 14, these individual challenges are summarized in the category "Other". Amongst these are:

- Increasing the number of customers and product installations
- Handling portfolio management

- Establish Systems Engineering as a new discipline in the organization
- Raising the acceptance of Systems Engineering in the organization
- Establishing SE leadership (strong coordination and controlling of responsibilities and activities)
- Handling the complexity of development
- Keeping up their innovation capability
- Coordinating Systems of Systems Engineering
- Supporting existing legacy software and transforming its further development to Systems Engineering methods

Q6: What are the future challenges related to Systems Engineering that your organization/unit will be confronted with in 5 years from now on?

For most organizations, the future challenges related to Systems Engineering are the same challenges they are confronted with today.

Additional future Systems Engineering challenges are highly diversified, depending on the application domain and the individual system development processes of each organization.

On the technical process level, these challenges range from model-based development via agile development or rapid prototyping to verification and validation with virtual prototyping and simulations. Better requirements and interface management for upcoming systems of systems was also mentioned.

On the project process level, new challenges such as introducing more product variants or keeping up the product quality (especially w.r.t. security and safety) are becoming more important. Here, SMEs have a special interest in data and information management and in introducing change management in the organization.

On the organizational process level, new challenges such as improved change management aimed at handling the transformation process of digitaliazation in the company or close leadership to really perform the Systems Engineering processes seem to be important. Some organizations plan to place more emphasis on human resources management in order to build up and preserve Systems Engineering know-how.

Figure 15 shows the highly diversified results regarding future Systems Engineering challenges in an overview.

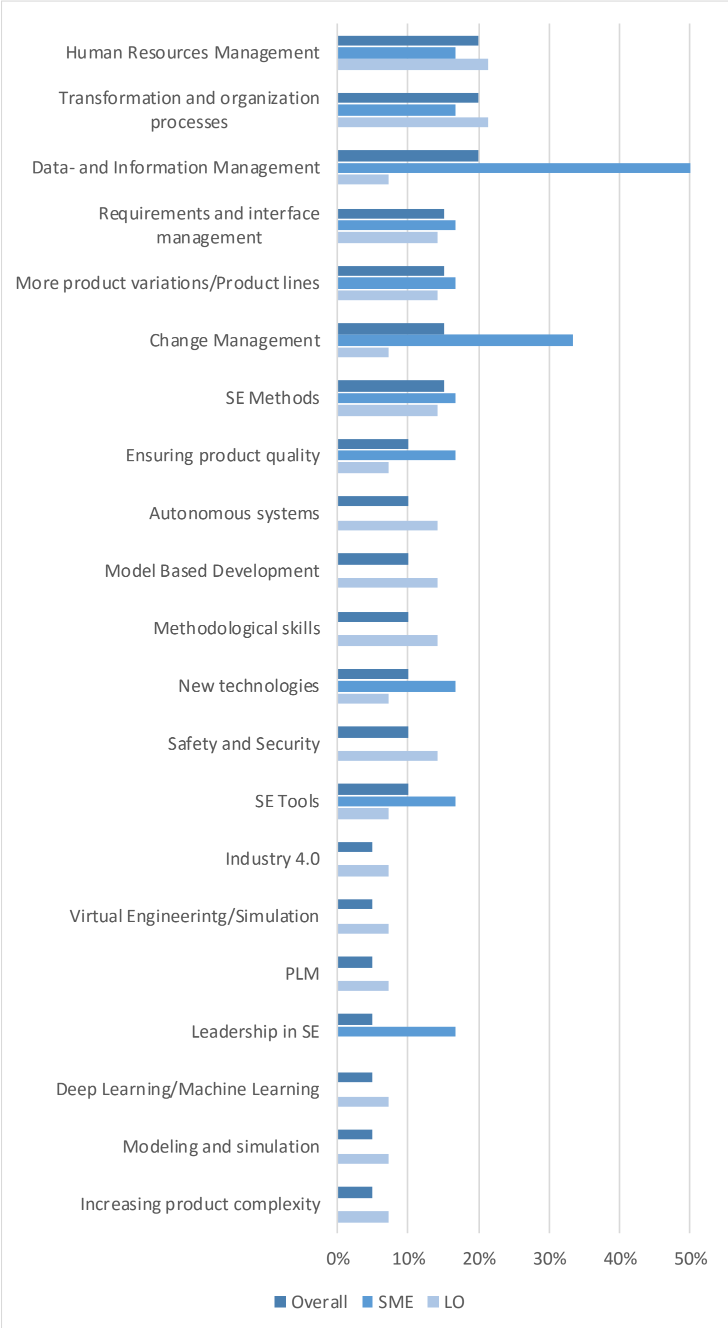

Figure 15: Future Systems Engineering challenges

No specific trend can be discovered here across the type or size of organization. Nevertheless, specific trends towards new functionality exist in individual application domains; e.g. in the automotive domain, autonomous driving creates new challenges for requirements and interface management for networked systems, modeling and simulations of products/solutions, and safety requirements.

2.3 Part 3: Solution Approaches

Q7: What does your Systems Engineering process look like?

A corporate Systems Engineering process ensures that all likely aspects of a project or system are considered and integrated into a whole. There are many Systems Engineering standards that have evolved over time, with ISO/IEC 15288 (Systems and software engineering -- System life cycle processes) certainly being the best-known international standard. The standard defines four process areas:

1. *Agreement Processes*: specify the requirements for the establishment of agreements with organizational entities external and internal to the organization [ISO15].

2. *Organizational Project-Enabling Processes*: ensure the organization's capability to acquire and supply products or services through the initiation, support and control of projects [ISO15].

3. *Technical Management Processes (Project Processes)*: are used to establish and evolve plans, to execute the plans, to assess actual achievement and progress against the plans and to control execution through to fulfilment [ISO15].

4. *Technical Processes*: are used to define the requirements for a system, to transform the requirements into an effective product, to permit consistent reproduction of the product where necessary, to use the product to provide the required services, to sustain the provision of those services and to dispose of the product when it is retired from service [ISO15].

The interviewed experts were asked for a general describtion of the company-wide Systems Engineering process, to the extent that a process was defined at all. In this regard, the given answers are not comparable with a regular process assessment, where experts assess the capability of an organization to meet the process goals in particular process areas.

However, 95% of the organizations have established Technical Processes in their entirety or in part. SMEs have a clear focus on systems requirement definition, the implementation process, and verification and validation. LOs have a broader portfolio because their Systems Engineering process in general follows given standards. The majority of larger organizations (85%) have established Agreement Processes (acquisition and supply) because these organizations act as system integrators by assembling product parts delivered, e.g., by SMEs.

All organizations (SMEs: 65%, LOs: 100%) carry out projects and have consequently established Technical Management Processes (project planning, control, risk management, configuration management, quality management). 93% of the larger organizations have implemented Project-Enabling Processes showing a systematic approach of carrying out Systems Engineering projects.

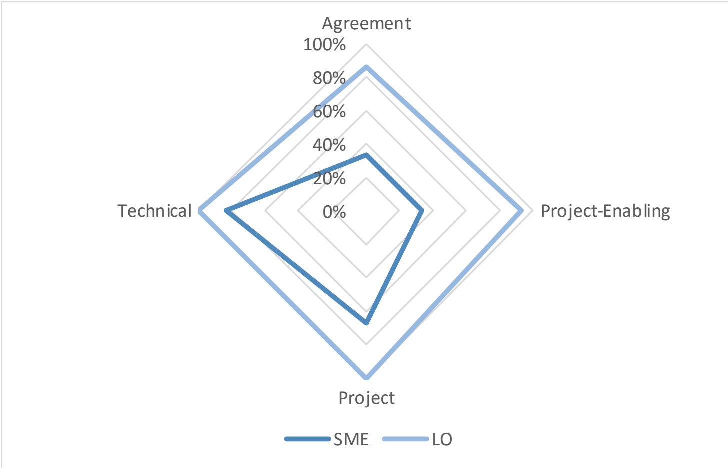

Figure 16: Systems Engineering process areas

Q7.1: What standards or de-facto-standards in the area of Systems Engineering are relevant for your organization/unit?

The V-model can be recognized as a de-facto-standard across the organizations regardless of their individual size. In addition, EN ISO 9001 gives guidance for SMEs to fulfill the minimal requirements to meet the needs of customers and other stakeholders in terms of product quality management.

Larger organizations that are more involved in Systems Engineering rely on the ISO/IEC 15288 standard [ISO15]. In the automotive domain, Automotive SPICE [VDA15] is used as a variant of the international standard ISO/IEC 15504. ISO/IEC 26262 for functional safety was also mentioned by the organizations as an important standard. Other mentioned domain-specific standards are IPC-A-600 and ISO/IEC 42010.

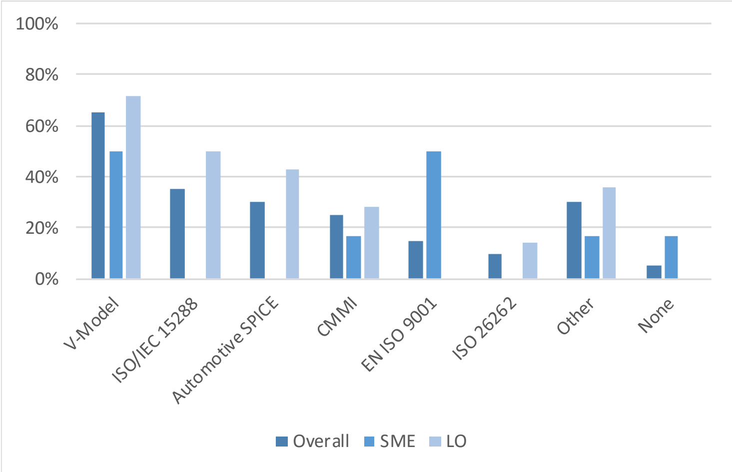

Figure 17: De-facto standards

Q7.2: What lifecycle model does your Systems Engineering process follow?

The most frequently used lifecycle models are the iterative resp. V-model for hardware development (70%) and agile for software development across all organizations (45%). 42% of the SMEs do not have any lifecycle model at all.

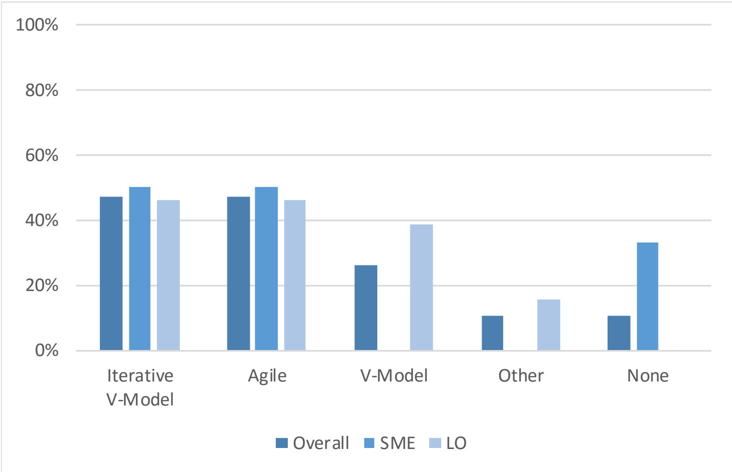

Figure 18: Lifecycle models

Q7.3: How many different variants of the development process exist in your organization/unit (is it standardized or are you following an individual approach)?

The majority of the SMEs (83%) have defined a common development process with little variants. In 86% of the larger organizations, several variants of the development process exist. However, as confirmed by the interviewees in LOs, a standard development process is defined. This standard process is tailord according to project needs. This explains the high number of variants shown in Figure 19.

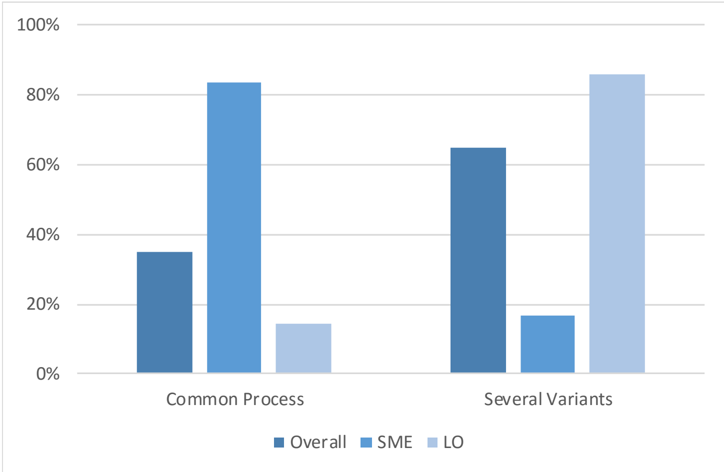

Figure 19: Process variants

Q8: How do you integrate multiple stakeholders/disciplines in Systems Engineering?

Q8.1: What disciplines/stakeholders exist in Systems Engineering in your organization/unit?

There are many different disciplines involved in the Systems Engineering process across all organizations regardless of their size. However, classic engineering disciplines like Hardware Engineer or Software Engineer are still viewed as "isolated" disciplines within the organizations. The particular discipline "Systems Engineer" is only defined within larger organizations (43%).

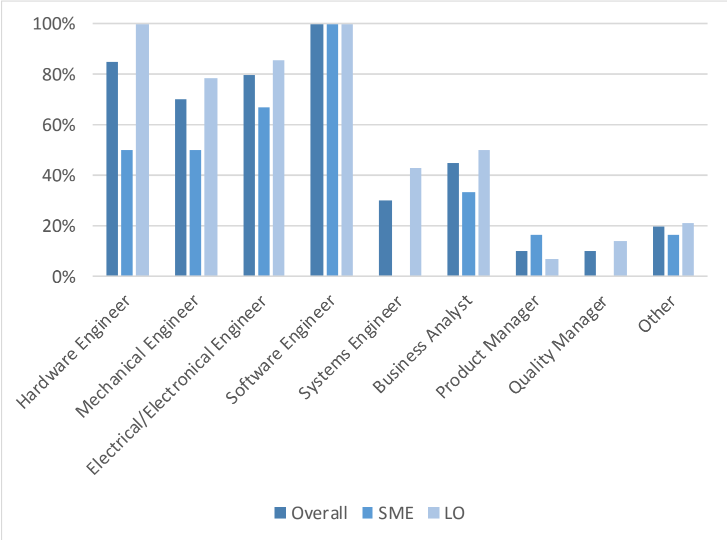

Figure 20: Systems Engineering disciplines

As shown in Figure 21, customer (85%) and supplier (75%) are the most important stakeholders across all organizations. Business units or other organizational entities are important stakeholders for 20% of the organizations. Authorities (government, local authorities, laws & regulations) are maily of interest to LOs (30%).

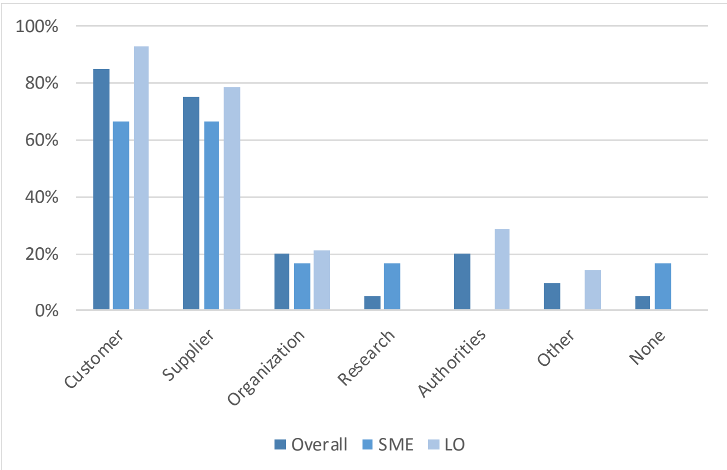

Figure 21: System Engineering stakeholders

Q8.2: How are the different stakeholders/disciplines interlinked and coordinated in your organization/unit?

In large organizations, the different stakeholders and disciplines are interlinked and coordinated by following a defined process (85%). Personal communication is the preferred way of smaller companies to organize their product development (20%). Personal communication includes making phone calls, writing emails, and holding face-to-face meetings. Team meetings on a regular basis are mentioned by 20% of the SMEs and by only 8% of the LOs. It may be that employees of a large organization are used to having meetings and did not deem them worthy of special mentioning.

Workshops and the creation of mixed teams to get a common project understanding are established in all organizations (SMEs: 80%, LOs: 57% resp. 50%). The use of tools and common data pools across organizational boundaries is an issue for all organizations (SMEs: 20%, LOs: 50%).

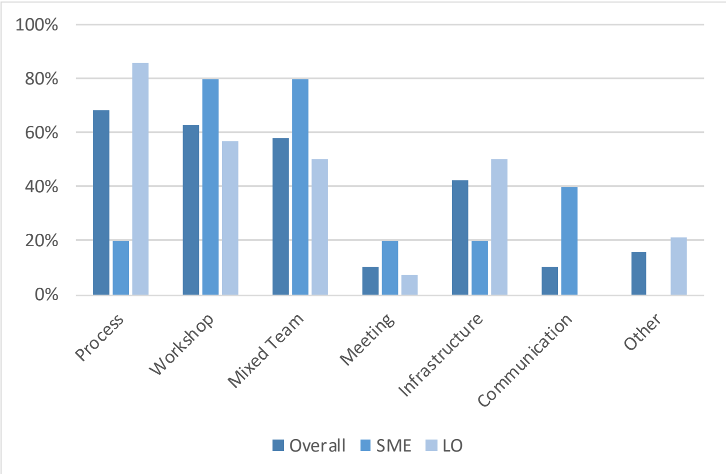

Figure 22: Stakeholder coordination

Q8.3: How do you integrate external suppliers into development activities in your organization/unit?

The integration of suppliers into development activities is mostly performed by supplier agreements (SMEs: 40%, LOs: 93%). A closer relationship is established by larger organizations through subcontractor management (43%). In addition, body leasing concepts are applied by LOs on a large scale (64%) to provide external knowledge for development activities. Training activities including workshops together with external suppliers are the means by which smaller organizations get a common understanding in development activities (40%).

20% of the SME's do not have any supplier in terms of hard- and software (cf. Figure 23).

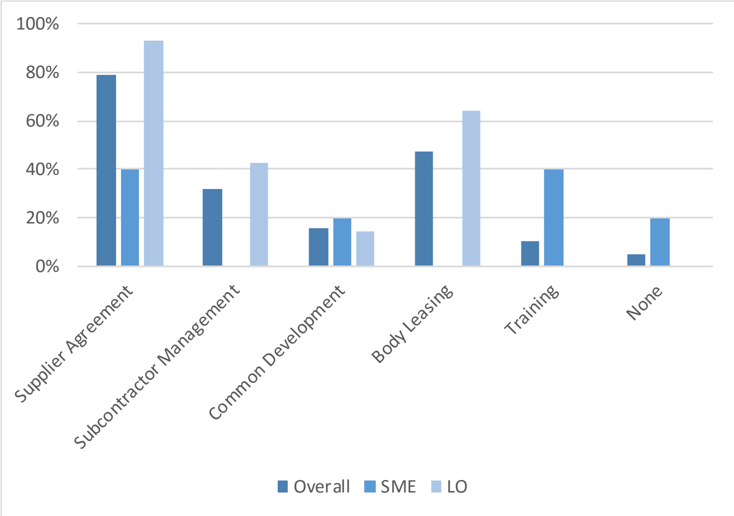

Figure 23: External supplier integration

Q8.4: What fraction of your product is supplied externally?

As shown in Figure 24, for almost 60% of the organizations, less than 25% of their product parts are supplied externally. Nevertheless, 26% of the organizations obtain up to 50% of the parts from external suppliers. The average proportion of externally supplied parts is about 25% across all organizations.

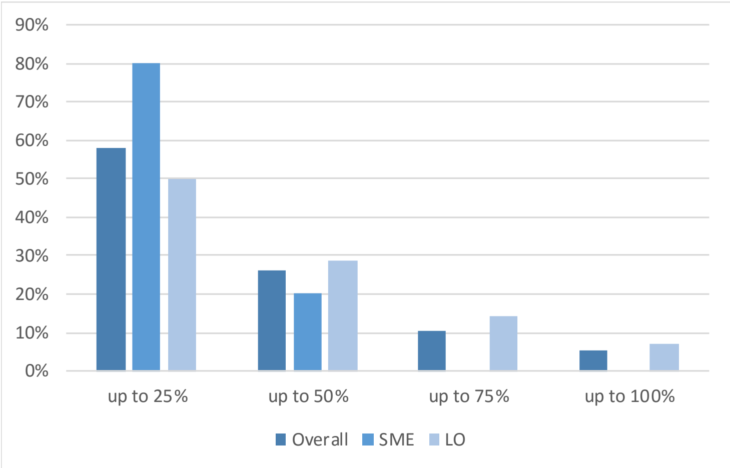

Figure 24: External production

In general, compared to SMEs larger organizations obtain more parts from external suppliers. As already discussed, this supports the assumption that LOs act as system integrators by assembling product parts delivered, e.g., by SMEs.

Q8.5: How would you rate the criticality of this fraction in terms of intellectual property? (on a scale from 1=not critical to 10=highly critical)

The majority (68%) of the SMEs rated this criticality with the value 1 because (1) the total number of externally supplied parts contained in SMEs products is very low compared to the fraction in LOs' products and (2) for the most part, SMEs integrate standard hardware.

Almost 60% of the larger organizations rated this criticality with a value greater than 3. Large organizations integrate externally supplied parts in substantial quantities. They maintain long-term business relationships with their suppliers to ensure predictable product quality and quantity.

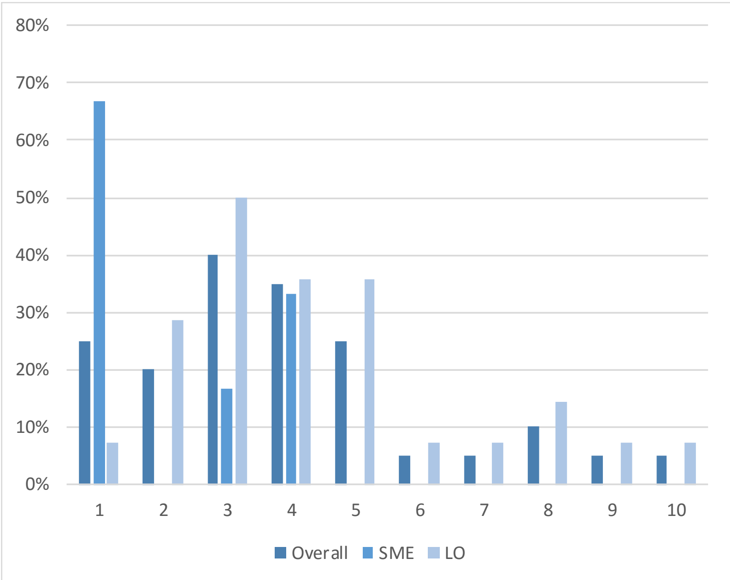

Figure 25: Criticality of external production

Q9: What are core established Systems Engineering practices?

A core Systems Engineering practice is defined as a method, technique, or approach that has been of high importance for implementing Systems Engineering in the organization.

Q9.1: What were the top 3 successfully established practices for Systems Engineering in your organization/unit?

As can be seen in Figure 26, from the already established practices, the companies largely (close to or more than 50%) picked methods, techniques, and approaches related to model-driven development, requirements engineering, test-driven development, and verification and validation. Further practices mentioned by at least more than one organization include integrated tool chains and virtual engineering, and an overall system architecture.

Moreover, the selection of the top practices varies between large organizations and SMEs. The variance is especially large for model-driven development and for system verification and validation, which were chosen by more than 60% and 80% of the large organizations, respectively, but only by less than 40% and about 50% of SMEs, respectively. More than 80% of the SMEs picked test-driven development as a top established practice. This was only picked by about 30% of the large organizations. Please note that this does not mean that large organizations do not do test-driven development; it only means that this was not picked as one of the top three practices.

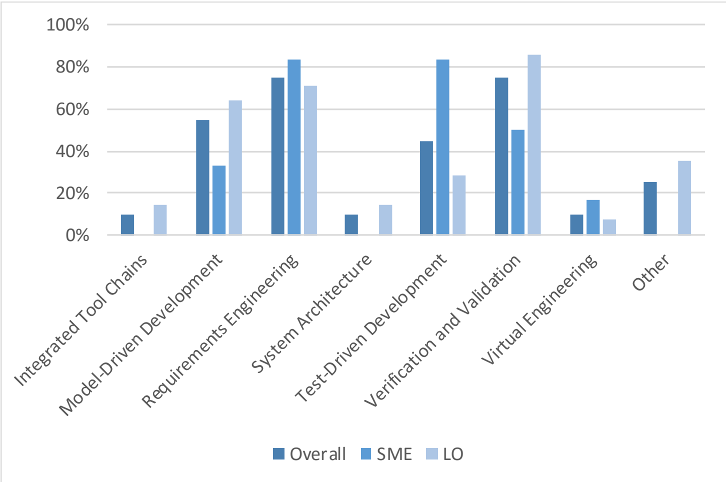

Figure 26: Top Established Systems Engineering practices

Q9.2: Which engineering processes are impacted by them?

Regarding the most strongly impacted process areas, the participants agreed with a huge majority that the technical and software implementation process areas (as defined by ISO/IEC 15288 and 12207) are impacted by the practices. This is also in alignment with the top practices mentioned above. As can be seen in Figure 27, the difference between large organizations and SMEs is mostly negligible when the overall number of participants is taken into account.

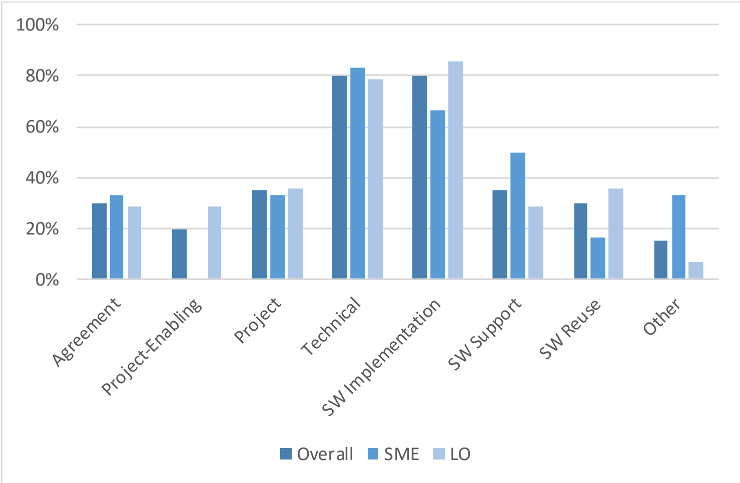

Figure 27: Impacted Systems Engineering process areas (ISO/IEC 15288/12207)

Q10: What technologies and tools are used for Systems Engineering?

Q10.1: What technologies and tools do you currently use to support the mentioned best practices in your organization/unit?

Even though the question asked for general technologies, mostly languages used for specifying systems were mentioned by the study participants. As can be seen in Figure 28, the majority – not surprisingly - referred to UML as the major relevant modeling language. Large organizations tend to use SysML (based on UML) as a more specific language for system modeling. Furthermore, some domain-specific languages were mentioned. Singular answers included DFD (Data Flow Diagrams), FMI (Functional Mock-up Interfaces), OSLC (Open Services for Lifecycle Collaboration), Structured Analysis, XML/XMI, IDef0, and Autosar.

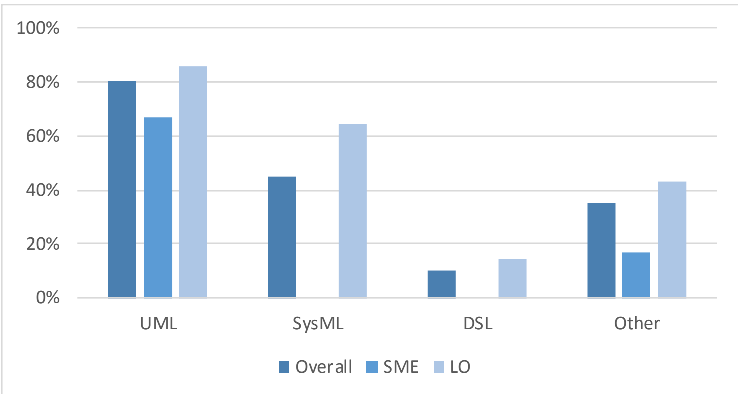

Figure 28: Specification languages used

Overall, more than 90 statements about tool usage related to Systems Engineering were made by the study participants (80% of them stem from large organizations) and over 40 different tools or components of tools were mentioned in these statements. Figure 29 gives an overview of the types of tools and how frequently tools of that type were mentioned.

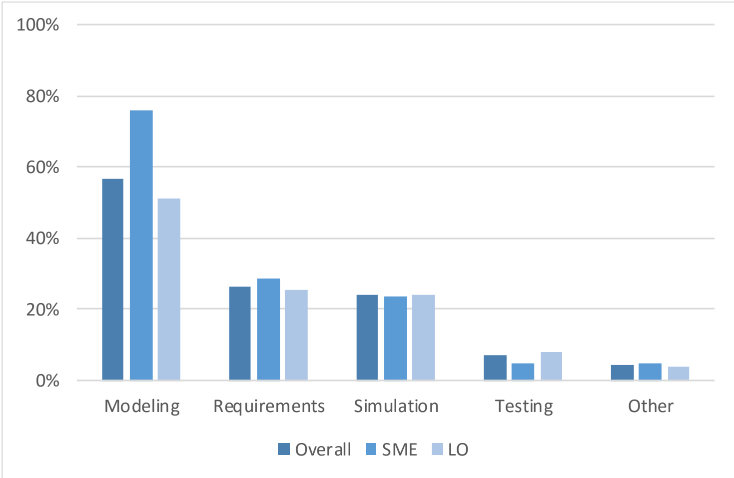

Figure 29: Types of tools for Systems Engineering

The vast majority of tools mentioned is related to modeling different aspects of the overall system or the software as part of the system. Depending on the domain, some tools were quite domain-specific (such as appropriate CAD software). Furthermore, mostly requirements-specific simulation tools and testing tools were mentioned to support the previously listed practices.

Regarding modeling tools, about 50% of the participants stated that they are using "Enterprise Architect" and "MATLAB". Regarding requirements tools, 30% use "DOORS" and "Microsoft Office". Regarding simulation tools, 40% use MATLAB's "Simulink" extension. Regarding testing tools, a variety of different tools were mentioned.

Close to 90% of the tools or components mentioned were specific for a certain type of activity, whereas a bit more than 10% were multi-purpose tools or integrated tool suites. Furthermore, close to 10% of the answers mentioned self-developed tools. Mostly these are used in the area of simulation (about 5%).

Q10.2: What emerging technologies could come into play in the near future?

Regarding emerging technologies, a variety of answers were given. Figure 30 shows the most frequently mentioned technological areas. The most prominent ones, with close to 40%, were the adoption of more formal methods and model-based system development approaches instead of informal/textual specifications. Furthermore, the general need for better integration of tool chains, virtual engineering incl. simulation, and the development of their own specialized tools were mentioned as technological areas for the near future.

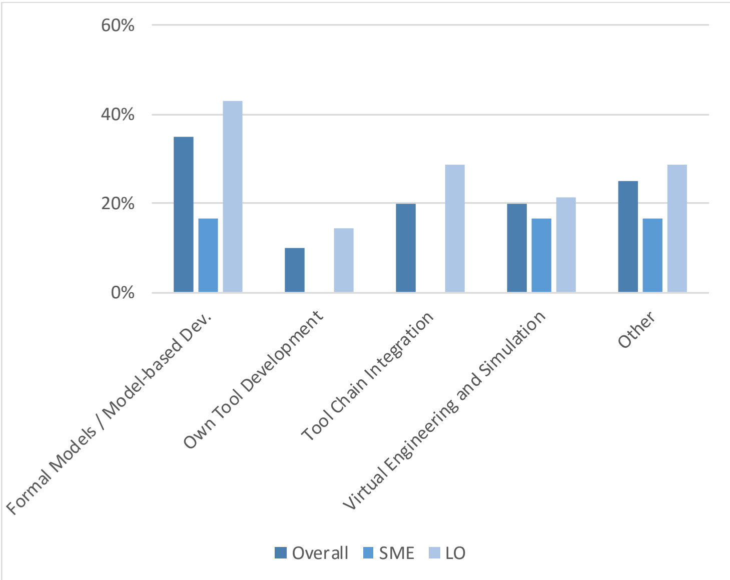

Figure 30: Emerging technologies and the needs to support Systems Engineering

Moreover, some general more product-/feature-related trends were mentioned that have an impact on the choice of technologies, such as Big Data, Internet of Things, and service orientation.

2.4 Part 4: Outlook and Capabilities

Q11: In which areas do you see the greatest improvement potential for Systems Engineering in your organization/unit?

As can be seen in Figure 31, the greatest improvement potentials for Systems Engineering, with more than 50% each, are in increased virtual engineering and better integration of the tool chains used. The demand seems to be bigger for SMEs.

For nearly 40% of the larger organizations, improved program management (aka. project portfolio management) is also worth mentioning. This is no surprise as larger organizations need to deal with a larger number of projects running simultaneously. For close to 40% of the SMEs, a higher degree of automation was seen as an important improvement potential.

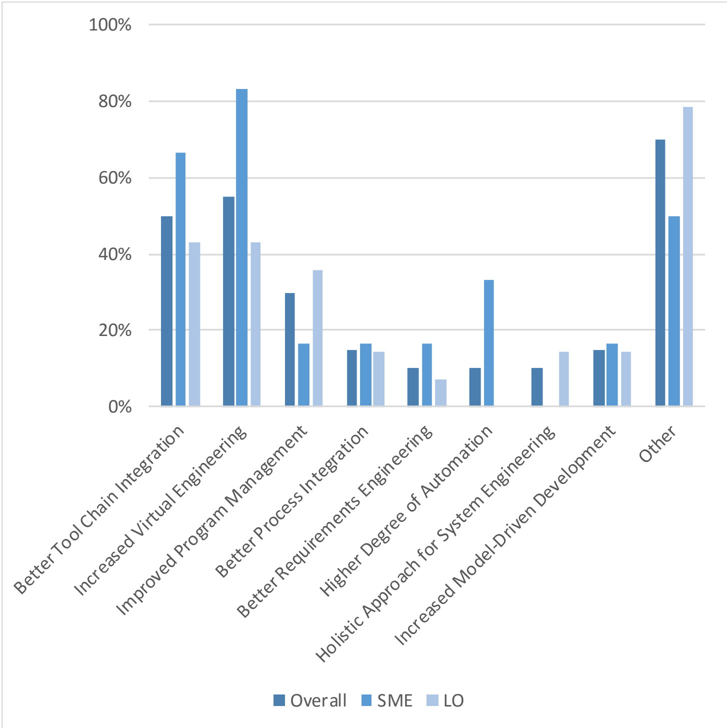

Figure 31: Areas of improvement potential for Systems Engineering

Q12: How does the organization/unit improve its capabilities regarding Systems Engineering?

Regarding ways to improve an organization's own capabilities in Systems Engineering, a variety of answers were given. However, as can be seen in Figure 32, the vast majority relies on making use of internal and external training programs. Not surprisingly, nearly all of the organizations offer such training programs internally. Furthermore, participation in Systems Engineering conferences for the purpose of exchanging knowledge and experience among peers and with researchers and discussions about trends and solution approaches was mentioned by more than 50% of the overall participants and by more than 60% of those from larger organizations.

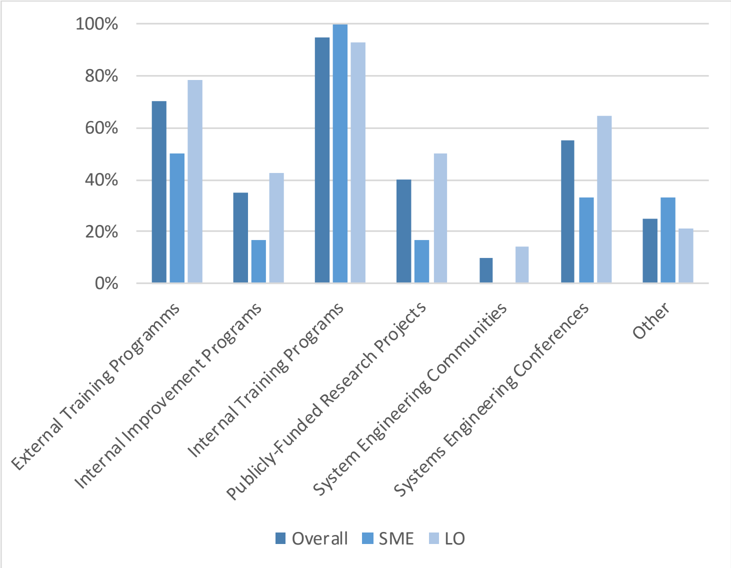

Figure 32: Approaches for improving System Engineering capabilities

3 Key Outcomes

The following key outcomes can be extracted from the 20 interviews based on our analysis:

(1) Product Engineering Trends: Companies are mainly driven by the increased complexity of system requirements (aspect stated by 60%) as well as by the ever larger number of product variations demanded by their customers (stated by half of the companies). In combination with shorter time to market (about 55%), this puts a lot of pressure on current system engineering. In the future, more cross-disciplined development is seen (by 20%) as an additional driving factor, which will in turn increase the complexity of projects. The trend to increasing cost pressure and shorter time to market is expected to remain.

(2) Importance of Software: More than 85% of the companies stated that software plays a major role in their products; even though about 70% of the participants stated that they come from a pure hardware development world. Furthermore, 85% stated that they spent 30% or more (up to 90%) of the development budget on software development. More than half of the participants agreed that this will further increase within the next five years.

(3) Importance of Systems Engineering: On a scale from 1 (not important) to 10 (essential for survival), the average importance of Systems Engineering is 7.6. Though Systems Engineering is currently already very important, this will increase to 8.7 within the next five years. Most participants stated that the reason for the increasing importance are customer demand for higher product quality in combination with increased complexity of the products. This especially refers to requirements related to system platforms and system integration.

(4) Systems Engineering Challenges: 80% stated that change management within the organization is the no. 1 challenge, followed by managing complex requirements and interfaces (especially for systems of systems). Additional future Systems Engineering challenges are human resources management, the transformation and organization processes regarding Systems Engineering within the organization and data- and information management.

(5) Systems Engineering Process: The larger organizations basically cover every process area of ISO/IEC 15288 and 12207, whereas the SMEs have a clear focus on the technical and implementation processes. The standards they adhere to are quite domain-specific, except for quite general approaches such as ISO

9001. 40% of the larger organizations explicitly referred to ISO/IEC 15288. Regarding the process models used, more than 45% of the large organizations and SMEs claim that they are following an agile model, whereas more than 50% of the large organizations follow a waterfall model or iterative waterfall model. Furthermore, more than 80% of the large organizations provide different variants of their standard process.

(6) Multiple Stakeholders: There are many different disciplines and corresponding stakeholders involved in the Systems Engineering process across all organizations regardless of their size. However, classic engineering disciplines like Hardware Engineer or Software Engineer are still viewed as "isolated" disciplines within the organizations. The particular role of "Systems Engineer" is only defined in larger organizations. In 85% of the large organizations, different stakeholders and disciplines are interlinked and coordinated by following a defined process. For SMEs, this figure is less than 20%. Instead, personal communication is the preferred way of smaller companies. Between 60% and 70% of the companies create joint teams and perform joint workshops and meetings for coordination purposes.

(7) External Suppliers: Almost 60% of the organizations get less than 25% of their product parts supplied from external sources. Nevertheless, one third of the organizations obtain up to 50% from external suppliers. The average proportion of externally supplied product parts is about 25% across all organizations. The average criticality in terms of intellectual property of externally supplied components is 3,5 on a scale from 1 (not critical) to 10 (highly critical).

(8) Systems Engineering Practices: Among the already established practices, the companies largely (close to or more than 50%) picked methods, techniques, and approaches related to model-driven development, requirements engineering, test-driven development, and verification and validation. Further practices mentioned by at least more than one organization include integrated tool chains, virtual engineering, and an overall system architecture. Whereas large organizations focus on model-driven development as well as system verification and validation, which was chosen by 60% and 80%, respectively, around 80% of the SMEs picked test-driven development as their top established practice.

(9) Impacted Processes: The participants agreed with a huge majority that the technical and software implementation engineering process areas (as defined by ISO/IEC 15288 and 12207) are mostly impacted by Systems Engineering practices.

(10) Specification Languages and Tools: More than 80% of the participants referred to UML as the major relevant specification language. Large organizations tend to use SysML as a more specific language for system modeling. Furthermore, domain-specific languages were mentioned in general. More than 50% of the Systems Engineering tools mentioned were related to modeling different aspects of the overall system or the software as part of the system. Furthermore, 30% mentioned requirements and 40% simulation tools as being relevant. Moreover, close to 10% of the answers mentioned self-developed tools. Mostly these are used in the area of simulation (about 5%). Moreover, close to 40% mentioned the adoption of more formal methods and model-based system development approaches instead of informal/textual specifications as a technological area to be addressed in the near future.

(11) Improvement Potential: The greatest improvement potential for Systems Engineering lies in increased virtual engineering and better integration of the tool chains used, with 50% of the participants mentioning each of these areas. The demand seems to be bigger for SMEs. For nearly 40% of the larger organizations, improved program management (aka. project portfolio management) is also worth mentioning. For close to 40% of the SMEs, a higher degree of automation was seen as an important improvement potential.

(12) Systems Engineering Capabilities: The majority of organizations/units rely on internal and external training programs (close to 100% and more than 60%, respectively) to improve the capabilities related to Systems Engineering. Furthermore, participation in Systems Engineering conferences was mentioned by more than 50% of the overall participants and more than 60% of those from the larger organizations.

4 Recommendations and Fields of Action

From the given 12 key outcomes of the study, a few recommendations and areas of activity can be derived for organizations striving towards Systems Engineering. Please note that these recommendations and actions are motivated by the study outcomes, but they are somewhat subjective as there may be other strategies for reaching the same goal.

We split the recommendations and areas of activity into those more closely related to organizational development and those more technically related to how organizations develop systems.

4.1 Organizational Development

(O1) Change Management Strategy: 80% of the companies stated that change management within the organization is the key challenge for Systems Engineering (see outcome #4). Therefore, it is important to openly think about which organizational structure and processes are best suited for coping with Systems Engineering challenges. In particular, it is important to include all stakeholders in that process in order to gain acceptance and to better motivate/communicate changes and carefully plan how these changes should happen (see outcome #6).

(O2) Systems Engineering Competencies: Creating internal and buying-in external training programs on different Systems Engineering topics was obligatory for the majority of organizations (see outcome #12). Additionally, we would recommend that organizations participate in Systems Engineering conferences and become active members of corresponding communities in order to get information about recent developments and exchange experiences regarding Do's and Don'ts (see outcome #12).

(O3) Software Engineering Competencies: As 85% of the companies stated that software plays a major role in their products although they come from a more hardware-oriented development world (see outcome #2) and as this will increase in the future, it is important for companies to build up or maintain an appropriate number of Software Engineering competencies. This number depends on the degree to which their product depends on software and what the major IP (intellectual property) and USP (unique selling point) of the company is. If the IP/USP is in software or is becoming software, it would make sense to build up their own resources in the area of Software Engineering. If software is only a means to an end, it makes at least sense to build up competencies for managing external software suppliers and partners (see outcome #7).

(O4) Project Portfolio Management: Larger organizations should place special focus on the management of the overall portfolio of their projects and the interconnections and dependencies among them, as this was mentioned as a special issue for improvement (see outcome #11).

4.2 Technical Development

(T1) Integrated Systems Engineering Approach: As time to market for new products is getting shorter and product complexity is increasing at the same time (see outcome #1), it is important to efficiently and effectively deliver value to the customers. Systems Engineering is considered very important for dealing with this issue, especially when it comes to system platforms and system integration (see outcome #3). This requires a well-integrated and aligned approach across all disciplines involved (see outcome #6). Especially when it comes to technical and implementation processes, companies should carefully think about what impact Systems Engineering has (see outcome #9) and – as there are no silver bullet approaches – what a custom-tailored process should look like that best fits the needs of the individual organization (see outcome #5).

(T2) System Requirements Engineering: The complexity of system requirements and the number of product variants has increased over time. As a matter of fact, in the near future they will further increase as (even) more cross-disciplined development will come into play (see outcome #1). This forces companies to think about how to elicit/develop requirements on the system level and how to manage them systematically over time. This also includes how to break them down into lower-level (especially software) requirements (see outcome #2).

(T3) Model-driven Systems Development: The study confirmed that model-driven development of systems is seen as a key practice for an organization. Larger organizations have already implemented it at least partially (see outcome #8) or see this as an essential improvement potential (see outcome #11). The actual use of formal modeling languages varies, even though there are very prominent ones such as UML and SysML. In the area of tool support, a variety of tools were mentioned as well (see outcome #9). An organization should therefore carefully evaluate which aspects of the system specification to model and what appropriate language and tool support is available. This tool selection should also be influenced by the interfaces provided by suitable tools to ensure seamless integration into the tool landscape of the development process (see outcome #10 and T6).

(T4) System Verification and Validation: Companies should think about establishing proper techniques and methods for system verification and validation and specifically for test-driven system development, as these areas were seen as crucial by many organizations (see outcome #8). Additionally, the development process should ensure that system verification and validation is properly linked to system requirements at all times.

(T5) Virtual Systems Engineering: As the complexity of products is increasing (see outcome #1) and development is becoming more multi-disciplined (see outcome #6), it becomes difficult and very cost-intensive to compose the different system parts physically. Therefore, companies should think about the feasibility of using virtual engineering systems based on sound models. In the future, this is seen as a major improvement potential for speeding up development (see outcome #11). Some companies have already introduced or developed their own simulation tools for system verification and validation (see outcome #10).

(T6) Integrated Systems Engineering Tool Chains: As we have observed, a variety of different tools are used for Systems Engineering in the organizations. Furthermore, companies have developed their own tools for particular tasks and for overcoming the shortages of existing tools (see outcome #10). One major point for improvement is better integration of the tool chains (see outcome #11)., Especially when starting to do Systems Engineering, companies should therefore put special emphasis on the interoperability of their tools and on having as much integration across the tool chain as possible.

5 References

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