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# The impact of specialized software on concept generation

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**Abstract**

Software implementations of traditional engineering design methods can potentially enrich the original methods. A study was conducted to better understand how concept generation can be facilitated using software. Participants of the study were asked to generate concepts using either specialized software, or by using traditional means, for applying function-means modeling and morphological matrices. A concept concretization metric was used to evaluate the results, which indicated that there are both positive and negative aspects of performing concept generation using specialized software.

*Keywords:* *design tools, early design phase, design space exploration, software tools, conceptual design*

## 1. Introduction

In the ongoing wave of digitalization, opportunities to convert traditional processes, tools, and methods into software have become more attainable. While converting already established design approaches into software can give rise to opportunities of enriching the pre-existing approaches, it first needs to be validated that this step into the digital realm has merit (Isaksson et al., 2020). Digitalizing and automating methods that have traditionally been conducted manually can have unintended side-effects (Martinsson Bonde et al., 2022). It is therefore necessary to conduct thorough evaluations of such digital tools to better understand the implications and address any negative consequences.

The Morphological Matrix (MM) (Zwicky, 1967) is a traditional engineering design method used to combine an assortment of ideas into concepts. This is typically done by decomposing the main functionality of the to-be product into sub-functions (SFs), and then identifying sub-solutions (SSs) to each individual SF. SSs can then be combined to solve each SF, and thus also the main function. While it was first proposed by Zwicky in the 60's, it has since been ever-present in literature used to teach the fundamentals of engineering design (Hubka, 1982; Pahl et al., 2007; Ulrich et al., 2020). However, the tools used to construct MMs have stayed relatively non-specialized. A common way of constructing the MM is using Excel, as seen in papers such as Gontarski and Scalice, (2021) and Ölvander et al., (2009). However, other non-specialized approaches for creating a visual representation of the MM exist, such as utilizing vector-based drawing tools, PowerPoint, or drawing by hand, as exemplified by Chagouri et al. (2021) and Almefelt (2005a). In an effort to provide a more specialized tool for constructing and using MMs, a software referred to as "Morpheus" was developed, the first version of which is open source (Martinsson Bonde, 2021). The aim of this software is to make it easier to create MMs, update existing MMs as new ideas are discovered, to keep track of incompatible SSs, and to maintain a list of possible combinations of SSs that can be further developed into concepts. This tool was initially introduced to first year mechanical engineering students. However, the quality of the output from Morpheus generated by the students was found to be quite low, in that the generated solutions were rarely developed beyond the mere combination of SSs identified using the MM (Martinsson Bonde et al., 2022). In the 2022 study, the students would often use Morpheus to generate an unmanageable quantity of SS combinations, and refrain from describing them any further. It was evident that the tool needed to be improved to better assist in systematically exploring the design space and motivate users to develop their combinations/solutions into concepts. Since then, a new version of Morpheus has been developed which has been designed around the results from the 2022 study. The refined version requires the user to utilize one out of three predetermined strategies for identifying solutions, which is intended to help users be more systematic and assist in reducing the design space to a manageable size. The users are guided through the process to minimize erroneous method application, and to make the tool easy to use even for novice designers. Additionally, it encourages the user to attach sketches to both SSs and solutions, and to describe all generated solutions to facilitate in the process of converting SS combinations into concepts.

Furthermore, a separate tool for Function-Means modelling (Tjalve, 1979) has been developed, which allows users to import their functional decompositions directly into Morpheus, supporting the connectivity between the function and solution space. Thus, the traditional approach of moving from functional decomposition into systematic concept generation can be facilitated within a single digital ecosystem. The research presented in this paper aims to improve the understanding of how the digitalization of traditionally non-specialized concept generation methods affects the outcome of the concept generation process.

## 2. Theoretical background

The MM method was developed by Fritz Zwicky, who used it (among other things) to demonstrate the potential for different jet engine design configurations (Zwicky, 1967), thus identifying hundreds of configurations that had not yet been considered. The method involves identifying each SF that a design needs to resolve its main function, followed by identifying SSs that can be used to resolve each individual SF. An SS can either be a concrete design solution, or a more abstract solution principle. As multiple SSs are identified for each SF, a discrete design space is created. Within this space, each unique combination of SSs, one for each SF, can potentially result in a new design concept. This idea has since been carried on by other authors, including Hubka, (1982), Pahl et al., (2007), and Ulrich et al., (2020). The SFs in the MM are typically generated through decomposition of some "main function". This is often referred to as a functional decomposition.

There are multiple approaches for how to conduct a functional decomposition. Common approaches include the block diagram and the function tree (Hubka, 1982). Typically, the designer first identifies the main function that needs to be fulfilled. Then, the designer searches for the SFs that are required to achieve the main function. This can be facilitated by studying a reference product that achieves the same (or a similar) main function as what the designer wishes to resolve (Pahl et al., 2007; Ulrich et al., 2020). A derivative method of the function tree is the Function-Means tree (F-M tree), which originally was conceived as a method for concept synthesis (Tjalve, 1979; Malmqvist, 1997). The F-M tree also includes the SSs (the "means") that are responsible for resolving each SF. Introducing more than one SS to an SF gives rise to alternative configurations, as an SF should preferably only be resolved by one SS (Suh, 1998). In other words, the F-M tree not only structures the functions of a technical system, but it can also be used to provide different ways of resolving those functions.

The SFs identified during functional decomposition are then typically used to identify SSs. At this point there are two key issues to keep in mind: 1) A combination of SSs does not equate to a design concept. As Ulrich et al., (2020) puts it, *"In no way does the mere act of selecting a combination yield a complete solution"*. Once a combination has been identified, it needs to be interpreted into a useful representation, such as a sketch and/or a textual description. 2) As the number of SFs and SSs within a morphological matrix increases, so too does the number of possible combinations. Consequently, it is often not possible to perform a "full combinatorial" approach in which all possible combinations are explored, due to time and cost limitations. The second issue intensifies the first issue, as the concept generation process becomes additionally cumbersome if every possible combination needs to be interpreted, sketched, and described. To mitigate this issue, it is often recommended to identify and omit infeasible SS combinations. However, this typically does not constrain the design space enough to enable a thorough



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exploration of each feasible combination. It has also been suggested that the SFs should be ranked by some metric, such as complexity (Almefelt, 2005a), and then prioritizing the highest ranked SFs during the combination process. In this paper, we will refer to this type of approach as a "pragmatic strategy". Pahl et al., (2007) mentions another approach which involves focusing exclusively on promising combinations, and establishing clearly why such combinations are of interest. This will be referred to as a "thematic strategy".

Other ideas for how to tackle these issues includes incorporating optimization to identify promising alternatives, as can be found in papers such as Ölvander et al., (2009) and Ma et al., (2017). However, this is only possible if detailed information of each SS is known. Pahl et al., (2007) points out that optimization in the early phases of design can be problematic, as not much is known about the concepts at this stage.

Despite the age of the MM method, there are still scenarios in which it is unclear how to use it effectively. This is especially true when navigating large discrete design spaces in the early phases of design. Some approaches involve optimization based on mathematical modelling of the SSs; however, such models may not be available in the early design phase. While multiple ideas exist to mitigate the issue, such as identifying incompatible SSs and applying different solution strategies, to the authors knowledge there has been no attempt to integrate these ideas into a comprehensive software framework, and study how it affects the outcome.

## 3. Aims and research question

The aim of this research was to explore the potential of a digital workflow in which specialized software (SSW) is used to map out a design problem and generate solutions. The software tested in this study has been designed to work together within a digital ecosystem, enabling the direct import of the functional decomposition into Morpheus to facilitate connectivity between the functional decomposition and the MM, as depicted in **Figure 1**.

The purpose of the software is to assist designers in their usual approach, while also strongly incentivising a systematic approach to concept generation through MMs. By requiring the users to utilize one of the three available solution strategies (full combinatorial, thematic, or pragmatic) the idea is that the designers will consider a larger region of the design space, and not discard potential solutions without deliberate intention or motivation. However, the implications of moving traditional engineering design activities to such a digital workflow are presently unknown. The intention was to answer the following research question: ***How is the quantity and quality of outcome affected by converting to a digital workflow in a concept generation activity?*** In this case, quality of outcome refers to the quantity and level of concretization of the generated solutions, and how many SFs were considered. By studying these performance indicators, it was possible to compare the outcome of a traditional concept generation exercise, and one that has been converted into a digital workflow.


F-M modeler

Morpheus (morphological matrix tool)

**Figure 1. The specialized software process**

## 4. Research method

To investigate the research question stated in **Section 3**, three independent in-person workshops were conducted. In the workshops, the participants worked with a concept generation task. After the workshop, each participant was asked to fill in a questionnaire with follow-up questions. The



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participants were 17 master's students from Chalmers University of Technology and 9 PhD students from the Technical University of Darmstadt. They were divided into teams of 3 or 4, forming a total of 8 teams (see **Table 1**).

**Table 1. Team partitions**

| *University* | *Total teams* | *Used specialized software* | *Used traditional means* |
|---|---|---|---|
| Chalmers | 5 teams | 3 teams | 2 teams |
| Darmstadt | 3 teams | 2 teams | 1 team |

These teams were tasked with generating new concepts for a coffee maker. The participants were provided with a document detailing their task, a small set of customer needs, and information about a reference product that the teams could use when performing functional decomposition. Three of the teams were tasked to do this without SSW; however, these teams were still allowed to use any other software (e.g., Excel and PowerPoint). The other five teams were instructed to use the SSWs for creating F-M trees (The "F-M modeler" software) and Morphological matrices (the "Morpheus" software).

## 4.1. Design study procedure

Shah et al., (2000) argue that to properly test a conceptual design method, there are two key things that need to be evaluated: 1) how effective the method is in expanding the design space, and 2) how well the method explores the design space. Shah et al., boils it down to four effectiveness measures: quantity, quality, novelty, and variety. Furthermore, Shah et al., points out that the environment in which the experiment is conducted should be as similar as possible for all participants. To enable the utilization of these four metrics, both sketches and textual descriptions are to be collected for all generated ideas. The initial intention of this study was to apply Shah's metrics for novelty and variety. However, as will become clear in **Section 5**, the generated concepts did not possess the attributes necessary to perform a thorough analysis of novelty and variety. As such, these aspects were disregarded in the final analysis.

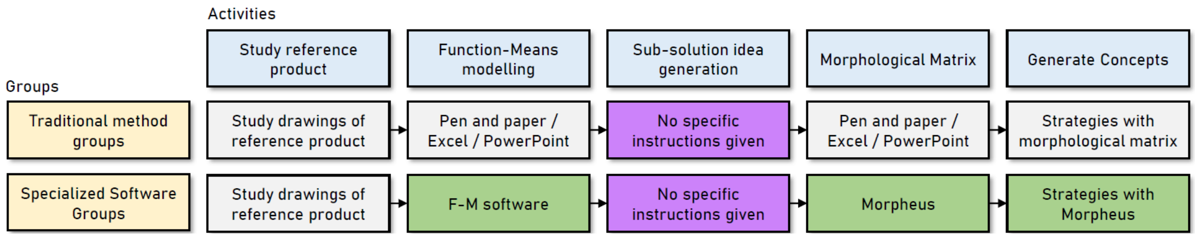


**Figure 2. The concept generation process undertaken by each team in the study**

Before the teams were allowed to start, they were instructed to watch an introductory video. This video contained a brief introduction to F-M modelling, MMs, and concept generation. At the end of the video, the task was introduced and the teams commenced the concept generation process as depicted in **Figure 2**, which is based on Ulrich et al., (2020) with the notable deviation of including function-means modelling (Gedell and Johannesson, 2013), as opposed to traditional function trees or flowcharts. The design problem is approached by identifying a main function that the product needs to solve, decomposing it into SFs, and then identifying SSs for each individual SF. The teams thus initiate the concept generation by performing a functional decomposition of a reference product using an F-M tree. The SFs that are derived from the decomposition activity are used in an MM. Finally, concepts are generated using the MM. To that end, some of the teams were assigned to utilize specialized digital tools for this process, while the remaining teams approached it through traditional means (drawing by hand, Excel, PowerPoint, etc.). To deal with the large number of possible combinations, the instruction video introduces the three strategies mentioned in **Section 2**: 1) the "full combinatorial strategy", which entails looking at every possible combination. 2) The "pragmatic strategy", which involves ranking the SFs based on importance, and reducing the number of SSs for the less important SFs. 3) The "thematic strategy", in which only SSs that follow a specified theme can be combined. As previously mentioned, these strategies were also implemented into the Morpheus software as *the only way* of generating



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combinations. In other words, those who used Morpheus could not manually create combinations; combinations could only be identified using one of the three strategies.

To analyse the results of the study for each individual team, three performance indicators were utilized:

1. Number of generated concepts or number of generated sub-solution combinations
2. Number of considered SFs in the MM
3. Level of concretization of solutions

A concept/solution, or combination of SSs, was counted regardless of the degree of concretization, as that was considered in a separate concretization metric. To the authors knowledge there has been no published works detailing how to evaluate the level of concretization of a design concept. Authors such as Hubka mention varying levels of concept concretization (Hubka, 1982), but does not define any specific metric for distinguishing individual levels. Thus, to enable such an evaluation, a rubric was defined before the tests. The rubric, presented in **Table 2**, was used to analyse all concepts generated in the study. The rubric contains four levels of concretization for textual descriptions of a concept, and five levels for visual descriptions. That includes a "level 0" for both metrics, which entails a lack of a sketch/description. In the case of visual concretization, levels 1 and 2 allow for individual SSs to be visualized to increase concretization of the final solution.

**Table 2. Levels (L) of concretization: descriptive and visual**

| *L* | *Descriptive criteria* ($C_{dsc}$) | *Visual criteria* ($C_{vis}$) |
|---|---|---|
| 0 | No description. | No sketches or images. |
| 1 | Array of nouns or principles. E.g., *"wheels, axis, engine"*. | Context-independent sketches/representations of the sub-solutions. The sketches/representations can be provided in the matrix itself. |
| 2 | Description of the relations of individual sub-solutions relative to each other. E.g., "*The wheels are attached on two axes. The wheels are rotated using the energy produced by a piston engine.*" | Sketches of sub-solutions with additional clarifying details relevant to the context. The sketches can be provided in the matrix itself. |
| 3 | Detailed description of the concept with additional details, aside from the relation of the combined sub-solutions. E.g., *"Two pairs of wheels are attached on two independent axes. The rear axis is driven by a piston engine, while the front wheel axis is non-driven, and arranged as an Ackermann steering geometry to allow the wheels to be angled."* | Sketch of the main solution principle. |
| 4 | *N/A* | Full concept sketch with additional details aside from the main solution principle. For instance, it might contain annotations to clarify elements of the sketch, or to describe measurements. |

In a few cases, when evaluating the output of the teams, only a fraction of the SSs was visualized. Such scenarios required a systematic approach to calculate the concretization level. The fraction of SSs represented by each level ($N_{li}$, where *i* is the level number), relative to the total number of SFs ($N_{sf}$) was multiplied by the value of that level (level 0 = 0, level 1 = 1, level 2 = 2), as seen in **Equation 1**. For instance, if an MM that contains 15 SFs has a solution which contains 10 SSs without visual representation, 3 SSs of level 1 concretization, and 2 SSs of level 2 concretization, then **Equation 1** would be used to calculate the visual concretization as such: $(10 \cdot 0 + 3 \cdot 1 + 2 \cdot 2)/15 \approx 0.47$.

$$\frac{N_{l0} \cdot 0 + N_{l1} \cdot 1 + N_{l2} \cdot 2}{N_{sf}} \approx \boldsymbol{C}_{\mathbf{vis}} \qquad (1)$$

Thus, the value of visual concretization ($C_{vis}$) can range from 0 (no sketches at all), to 4 (full concept sketch), and the descriptive concretization ($C_{dsc}$) can range from 0 (no description) to 3 (detailed description). However, as long as a combination of SSs have been identified, then the descriptive concretization will count as a "level 1" description. Since combinations of SSs is the simplest form of output from an MM, none of the generated combinations could possibly be of "level 0" in terms of



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descriptive concretization. Using this approach, the level of concretization could be represented numerically for any scenario. Additionally, to provide an overview of team performance, a unified metric for concretization was created by combining $C_{\text{vis}}$ and $C_{\text{dsc}}$ into a normalized concept concretization metric $C_{\text{n}}$. The contribution of each concretization variable was divided by its highest possible value and then averaged, according to **Equation 2**, thus forming a normalized metric $C_{\text{n}}$, which can range from 0 to 1.

$$\frac{C_{\text{dsc}}/3+C_{\text{vis}}/4}{2}=C_{\text{n}} \qquad (2)$$

Consequently, a $C_{\text{n}}$ value of 1 would indicate full level of concretization in both the visual and descriptive aspects, according to the rubric in **Table 2**. However, since level 1 descriptive concretization is the lowest a combination outputted from an MM can achieve, as previously motivated, $C_{\text{n}}$ will in this case never be lower than 0.17. To be clear, there is no firm concretization threshold where a combination of SSs can be thought of as a "complete concept/solution", but a higher $C_{\text{n}}$ is favourable.

## 4.2. Individual participant questionnaire

Each participant was asked to answer a questionnaire. The questionnaire aimed to gather data on the participants' self-assessment of the utility, efficiency, and usability of their applied approach, Morpheus-supported or not. The questionnaire was comprised of questions related to respondent categorization (e.g., level of pre-knowledge, and whether they used the SSW), applied work practices (how solutions were searched for and integrated), results (quantity, quality, innovativeness, and variety of generated solutions), and finally efficiency of the support given by the applied methods and tools. The statements related to results were based on Shah et al. (2000) and Ulrich et al. (2020) criteria for a set of solutions that is likely to include excellent solutions. The statements related to efficient support methods were based on characteristics of efficient design methods as proposed by Norell Bergendahl, (1992), Araujo, (2001), and Almefelt, (2005b). In total, the questionnaire included 23 questions/statements. Some of the key questions covered by the questionnaire are listed in **Table 3**. Some of the participants failed to send in the questionnaire response. A total of 24 responses were collected (96% of participants).

**Table 3. Key questions posed in the questionnaire**

| *Question* | *Available answers* |
|---|---|
| My team addressed the task | With/Without SSW |
| Prior to the study, I would assess my proficiency in the application of concept generation methods as | Novice; Intermediary;<br>Advanced;<br>I don't know |
| We managed to map out the full solution space for coffee maker designs | **Likert scale:**<br>I don't know;<br>Strongly disagree;<br>Somewhat disagree;<br>Neutral;<br>Somewhat agree;<br>Strongly agree |
| We generated a large number of innovative concepts (according to your own estimation) | |
| The methods and tools that we used were easy to learn, understand and apply | |
| The application methods and tools that we used resulted in a time-consuming concept generation activity | |

## 4.3. Analysis of results

The data collection resulted in two sets of data. The output from the workshop (F-M trees, MMs and the list of concepts with sketches and descriptions) were inspected by the first author and codified using the performance indicators outlined in **Section 4.1**. The SurveyMonkey tool was used to support univariate and multivariate analysis of the data from the questionnaire. The data was perused both to validate assumptions concerning the use of the digital tools (e.g., that teams using digital tools would generate a higher number of alternative concepts) as well as to explore some less understood effects (e.g., if use of digital tools leads to generation of more innovative solutions). Two multivariate analyses were carried out, which focused on differences between subgroups that differed with respect to 1) use or no use of the SSW, and 2) levels of previous experience with concept generation. It should be noted that the results



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gathered from the workshop and the questionnaire were not varied enough, and not of a high enough quantity, to yield statistical significance. Thus, the findings will merely be used as basis for discussion, rather than drawing any strict conclusions.

## 5. Results

In this section we will present the results of the workshops, and the questionnaire.

### 5.1. Workshop results

The results from each team have been summarized in **Table 4**, which has been sorted by the approach applied by each team. The approach was either "Traditional" (Trad., in table), or using SSW. The team names start with either S, as in "Swedish team", or "G", as in "German team".

**Table 4. Team results**

| *Team* | *Appr* | *Comb* | *SFs in matrix* | *Design space (unconstrained)* | *Strategy* | $\bar{C}_{dsc}$ | $\bar{C}_{vis}$ | $\bar{C}_n$ | *Time [h]* |
|---|---|---|---|---|---|---|---|---|---|
| G1 | SSW | 16 | 23 | 5,4675E+12 | pragmatic | 1.00 | 0.50 | 0.23 | 3 |
| G3 | SSW | 64 | 31 | 3,5831E+13 | pragmatic | 1.00 | 0.00 | 0.17 | 3 |
| S1 | SSW | 4 | 19 | 6144 | pragmatic | 1.25 | 4.00 | 0.71 | 3 |
| S2 | SSW | 24 | 6 | 432 | thematic | 1.00 | 2.00 | 0.42 | 3 |
| S4 | SSW | 3 | 15 | 1728 | pragmatic | 1.00 | 0.00 | 0.17 | 2.25 |
| G2 | Trad. | 1 | 24 | 2,4766E+12 | unknown | 1.00 | 3 | 0.54 | 3 |
| S3 | Trad. | 2 | 15 | 13824 | unknown | 3.00 | 0.40 | 0.55 | 3 |
| S5 | Trad. | 2 | 5 | 24 | thematic | 2.50 | 1.7 | 0.63 | 2 |
| *Max:* | | 64 | 31 | 3,5831E+13 | N/A | 3.00 | 4.00 | 0.71 | 3 |
| *Min:* | | 1 | 5 | 24 | N/A | 1.00 | 0.00 | 0.17 | 2 |

For each team, the number of generated combinations was recorded. As previously mentioned, a combination is a set of SSs that fulfil the criteria of there being a one-to-one mapping with the set of SFs. It counts as a combination regardless of whether there exists a sketch or a more elaborate textual description of that combination. Notably, the teams who did not use SSW generated fewer combinations than those who used SSW. On the other hand, the average level of normalized concept concretization for the traditional teams ($\bar{C}_{n,trad} = 0.57$) was higher than for the SSW teams ($\bar{C}_{n,SSW} = 0.34$). However, the team with the highest level of normalized concept concretization was an SSW team (S1), who produced a full concept sketch for each of their 4 concepts. The team who generated the largest number of combinations had no sketches at all. However, they did have the largest number of SFs in the MM, the largest unconstrained design space, and the lowest concretization level. Notably, the German teams had more SFs than the Swedish teams, and a lot larger unconstrained design spaces.

None of the teams elected to attempt a full combinatorial solution strategy, as this would likely have generated far too many concepts to be manageable. It should also be noted that two of the traditional teams did not disclose what strategy they employed to identify their concept(s). That does not mean that no strategy was used, but it does mean that the documentation of these approaches was lacking. Conversely, the concepts generated using SSW were all automatically decorated with meta-data containing information about the approach undertaken by the participants.

Finally, two of the teams did not use all the time that was available to them (S4 and S5). The rest of the teams used all time that they were given, and often had to stop before being able to finish.

### 5.2. Questionnaire results

In the introduction of the questionnaire, the participants were asked about their perception of their own level of experience with concept generation methods. Seven of the participants regarded themselves as



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novices, 13 as intermediate users, three as advanced users, and one participant was uncertain. Thus, most of the participants considered themselves to be familiar with the methods in the experiment.
The chart in **Figure 3a** shows the perceived difficulty of learning and applying the methods and tools used in the design study. Those who utilized the SSW found it easy to learn and use, while those who applied the traditional approach had some minor issues. **Figure 3b** shows that those who did not use SSW typically perceived the application of the methods and tools as time-consuming in the context of the design study. On the other hand, those who used SSW had a more spread-out opinion regarding the time-efficiency of applying the tools. The level of previous experience did not have a significant impact on how the participants answered this question.

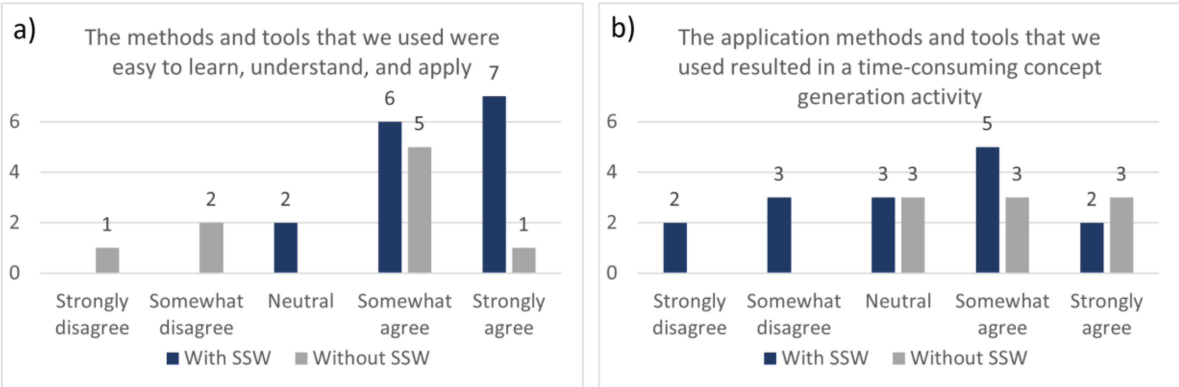


**Figure 3. Methods/tools ease of use**

The other questions posed in the questionnaire did not yield noteworthy results that indicated anything beneficial or negative towards the use of SSW, aside from a slightly negative tilt regarding the perception of how innovative the concepts generated by each team was. When asked if the participants thought that they had "generated a large number of innovative concepts", those who did not use SSW were slightly more positive regarding their ability to identify innovative concepts.

## 6. Discussion

The SSW teams all generated more combinations than any of the traditional teams. It could thus be argued that the software enabled the consideration of more design alternatives. However, it is not necessarily that clear-cut, as the concept concretization levels suggests. The question is, did the teams truly consider a design concept if its combination of SSs was not developed beyond the lowest levels of concretization? As mentioned in **Section 2**, a combination of SSs does not automatically translate into a concept. Rather, the concept needs to be elicited from the combination of SSs through interpretation to reach an appropriate level of concretization. One possible explanation might be that since the SSW teams generated more combinations, those teams needed more time to reach higher levels of concretization for all their concepts. Since time was very limited, and most teams used all time available to them, it may be the case that the SSW teams simply generated too many combinations to properly concretise within the given time. This might also explain why some of the participants who used SSW perceived their output as less innovative relative to those who applied the traditional approach.
The task was intentionally designed to be of high complexity by encouraging the participants to consider many SFs, which naturally resulted in large design spaces as the teams brainstormed ways to solve each SF. On average, the traditional teams considered 14.7 SFs, while the average for the SSW teams was 18.8 SFs. Thus, the teams were required to spend a lot of time reducing the considered design space. The traditional teams seemed to get around this mainly by focusing on one or two possible combinations, but generally failed in disclosing why only those combinations were considered. Conversely, since the SSW teams were required to apply one of the available strategies and identify incompatibilities until the design space was small enough, it required them to make decisions such as "which SSs for this SF can we disregard?". This likely also factored in to why the SSW teams had more combinations, but less concretization, as more time was allocated to systematically delimiting the design space.



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One additional noteworthy point of discussion is the quality of documentation. This varied significantly between the traditional teams, while those who utilized SSW naturally produced a very specific format. In some instances, the documentation created through traditional means was difficult to parse, while the SSW-output was generally quite easy to import back into the tools for review. One of the more extreme examples of difficult-to-parse output compared to a typical SSW output can be seen in **Figure 4**, where a hand-drawn F-M tree is compared to an F-M tree created by one of the SSW teams. Taken together with the fact that it was difficult to discern what strategy two of the traditional teams had undertaken due to their lacking documentation, it seems to indicate that utilizing an SSW-approach has beneficial effects on the quality of the produced documentation.

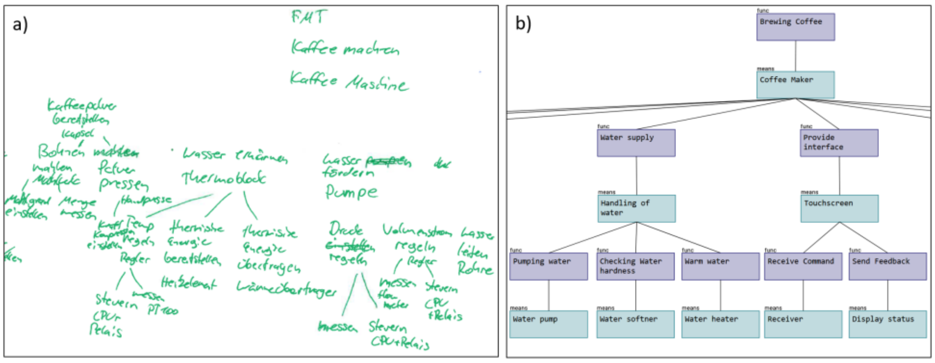


**Figure 4. F-M tree result examples: hand-drawn to the left and using SSW to the right**

Regarding the research question, *"How is the quantity and quality of outcome affected by converting to a digital workflow in a concept generation activity?"*: since statistical significance could not be achieved, firm conclusions cannot be drawn. Despite this, there has been some interesting points for further discussion. Although a similar number of SFs were considered, the SSW teams encountered a larger quantity of combinations. The SSW did not allow the teams to manually select solutions, only reduce the design space through application of the strategies available in Morpheus. Consequently, the SSW teams were compelled to discuss the different design alternatives and make decisions regarding which SSs to omit, and which to keep. At least that was the intention with the SSW, as such discussions may encourage the user to consider the SSs within the relevant context, thus improving their understanding of the design space. Regardless, the level of concretization for the SSW teams was lower on average, compared to the traditional approach.

Even so, the update to the Morpheus software seems to have partially fulfilled its purpose, which was to assist the users in reducing the design space to a more manageable size, and to aid users in being more systematic in their approach. While the SSW teams on average had a low level of concretization, they did manage to successfully reduce their design spaces to manageable sizes while maintaining a systematic approach. Nevertheless, further enhancements and studies need to be made. The users need to be further incentivised to concretise their solutions. A more efficient systematic approach to exploring the discrete design space could be developed to let designers allocate more time to concretization. Additionally, a future milestone is to test the SSW together with industrial partners to investigate how it could be adapted to their needs, and how it would impact the workflow of experienced designers.

## 7. Conclusions

A design study was conducted with master's student from Chalmers University of Technology in Sweden, and PhD students from Darmstadt University in Germany. The participants were grouped into teams of 3-4 people and asked to generate concepts for a coffee maker. Some of the teams were asked to use SSW to facilitate the functional decomposition and construct an MM, while the other teams were allowed to use traditional means such as Excel, PowerPoint, drawing by hand, etc. The outcome of the design study was a concept catalogue, which for each team contained a set of combinations of SSs identified using the MM, along with sketches and descriptions of each combination/solution. Arguably, to turn a combination of SSs into a concept, additional definition and details are required. Thus, a metric for concept concretization was proposed and applied when analysing the results.



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Though statistical significance could not be achieved in this design study, the findings can be used to spark a discussion regarding the digitalization of traditional methods and tools. The results from the post-experiment questionnaire seem to indicate that the participants found the software to be easy to use, perhaps even easier than the traditional approach. However, there is still a difference in outcome when using SSW compared to using the traditional approach. The participants who used the SSW generated more combinations than the traditional teams, though these combinations were often lacking in concretization. This may be a result of the teams identifying more concepts than they had time to define, as the time constraints of the experiment were purposefully short and strict.

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