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Framework to Redesign Products with focus on Design For Assembly Meaning: a PBL Case Study

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In many companies and especially in companies producing small series of products, manual assembly is highly needed for its flexibility. Complexity of manual assembly tasks is increasing in these companies and operators need to be supported. A framework was developed to facilitate designers to design for assembly meaning, a product design approach that aims to improve the intuitiveness of the assembly process and tries to lower the need for procedural instructions. In this paper, a project based learning (PBL) case study was used to assess the framework. In this study, twenty-eight students redesigned six light fixtured based on the analysis of the assembly process and in close cooperation with the company. The results of a survey taken from the students showed that the framework was valued by many students within a PBL setting. Moreover the solutions designed by the students to foster a more intuitive assembly were valuable, mostly feasible and showing a variety of solutions. The added value of offering a framework to design for meaning in assembly and to implement this in a PBL setting with access to a company, operators, products and prototyping facilities was also illustrated. The framework, method and tools are all discussed within the context of project based learning.

Keywords: Product design, assembly, project based learning

1. Introduction

This paper discusses a case-study where design engineering students used a framework to redesign products with a focus on Design for Assembly Meaning (DFAM) and this in close cooperation with a company and within a project based learning (PBL) setting. The goal of the case-study was to gather insights, first on the quality of the solutions generated by the students and secondly on how the framework was used and evaluated by the students in a project based learning setting with real products and a real company. This case study is a first case study to research how DFAM can be integrated in design engineering education and how it is evaluated by the students when applying it in a PBL setting. The results can offer insights to improve the framework, the associated tools and the implementation in PBL courses. Moreover, when evaluated positive, this could give arguments to integrate DFAM in addition to Design for assembly (DFA) in design engineering educational programs.

1.1. DFAM in design education

DFAM is a product design approach that focusses on how the design of a product can promote the construction of an appropriate mental model of the assembly process by the operator, eventually supporting the operator during assembly [1]. This approach aims to increase the intuitiveness of the assembly process and by doing so to decrease the need for procedural instructions and the associated drawbacks. A first drawback can be found in the tendency of operators to not use the procedural instructions but to rely on own experience or experience of others [2]. According to Fast-Berglund et al.[3] this tendency is in some cases prevalent for over 60% of all the tasks. Secondly, procedural instructions can increase cognitive load because the operator is forced to memorize the information and mentally integrate it with the physical objects (e.g., components, subassemblies, tools, etc.) in order to understand how to proceed the assembly. This so called split-attention effect is caused by divided attention and mental integration [4]. Finally, these types of instruction can potentially have negative effects on work motivation and even on mental wellbeing of some operators because these instructions can frustrate the need for autonomy. Autonomy, competence and relatedness are basic psychological needs correlating with self-motivation and mental well-being (see Self-Determination Theory, a robust and widely applied motivation theory in psychology, see [5]).

To tackle the drawbacks of procedural instructions, DFAM was introduced and defined by Parmentier et al. [1, p. 5] as: "*. . . a framework that offers designers insights to design products that support the assembler in constructing an appropriate mental model of the assembly process when interacting with components, subassemblies, tools, jigs, fixtures and the assembly environment*". As described in this paper, DFAM especially focusses on affordances (i.e., action possibilities) and product semantics (i.e., meanings associated with product features) when considering meaning in an assembly context. However, S. U. Boess [6] pointed out that these theories are hardly known or used by product designers in industry and that they more or less rely on intuition when considering design for meaning in the context of use. Nevertheless, a previous case-study in which design engineering students were offered a framework to consider affordances and product semantics more explicitly when focusing on design for meaning (i.e., to design products of which the use is easily understood) illustrated the added value of using a framework within a Project Based Learning (PBL) setting, see [7]. These results trigger the question whether students are also capable of using a more specific framework to design for assembly meaning in a project based learning setting and how this framework would be valued by the students. When considering design for meaning, design engineering students (certainly the students of the education program in which this research took place) are trained to consider product use and the potential interactions of the end-user with the product. In contrast, when considering DFAM, the students are much less familiar with how meaning is constructed by an operator during the assembly of the product (i.e., when interacting with the components, subassemblies, tools, jigs and fixtures). Nevertheless, not considering DFAM can have important implications for the assembly process, e.g., products that are difficult to assemble, frustration and demotivation of the operator, more time spent on the assembly, lower performance, more costs, more assembly instructions needed, etc.

Considering the operator and how the operator constructs meaning during interaction with components, subassemblies, tools, jigs and fixtures can thus be valuable. Therefore it could be very important to educate designers to consider DFAM and learn them how to implement it in their design processes. Therefore, integrating DFAM in design education programs can be an interesting step to bridge the gap between designers and assembly operators. However, before considering the integration of DFAM in an education program it is important to research how it can be used in PBL courses (PBL allows implementation of the framework in a design project setting) and which results the students achieve when they use it with real products and within a real existing assembly context. Insights on the usability of the framework to implement DFAM – i.e., to design or redesign products, components and subassemblies that promote an appropriate mental model of the assembly process and in relation to tools, jigs and fixtures – and its evaluation by the students are important.

1.2. DFAM during PBL

In PBL (for design projects sometimes more specifically mentioned as design based learning) emphasis is set on the resemblance of the design activities with real design activities and within real engineering settings, see [8 - 10]). This emphasis is important because it allows students to experience and build knowledge in settings that resemble realistic future working settings. As a consequence, PBL facilitates contextual learning (coined as problem-based learning by Abrandt Dahlgren [11]). Moreover, PBL gives students the opportunity to iteratively learn through experience while receiving the necessary knowledge [12]. Furthermore, this is achieved without negative effects on other forms of learning such as understanding of concepts and principles [13].
The integration of PBL and formal instruction sessions appears to be very valuable for generating sound solutions for technological problems [14]. This integration of more formal and practical aspects is also important to design for assembly meaning in a PBL setting. Before being able to apply DFAM, students have to know affordances and product semantics (these are related to Design For Meaning). Therefore the students received a lecture on affordances and product semantics (Design For Meaning) and on DFAM in the first week. Also in the following weeks, specific formal sessions were planned where a methodology and tools were presented for DFAM (e.g., for analysis of the assembly process, for searching solutions, for converging into a final solution). These sessions were planned in line with the progress of the project, offering the method and the tools to help solving problems and foster progression. This problem-solving ability is also linked to active learning strategies because these strategies are needed to acquire new knowledge that is needed to progress. As discussed by De Graaff and Kolmos [15] it is crucial for students in a PBL curriculum (i.e., both problem-based or project based) to take responsibility for their learning process and to become lifelong learners. Active learning was also a specific skill that was indicated by Karaman and Celik [16] as a skill that can be acquired by students in PBL environments. This skill is very important for design engineering students because they want to create, improve and develop products for which in many cases they cannot fall back on existing knowledge. PBL also offers researchers the possibility to gather insights on the applicability of the framework in a design project and to fine-tune the framework based on the results and feedback of the students. An important aspect of PBL is that students experience themselves and iteratively build the knowledge. Following, the role of the lecturer in PBL projects is typically a more facilitating, supportive and coaching role [17, 8].

In the following sections we will first discuss the different tools that were offered to the students (i.e., to analyze an existing product and assembly process with a focus on DFAM and to search, select or combine solutions). Finally, we will discuss the method followed in this case study and the results.

2. Tools for DFAM

To design products with a focus on assembly meaning, different design phases with a focus on DFAM must be followed. In a first phase the existing product and assembly process must be analyzed in order to identify difficulties or opportunities for improvement. Secondly, different solutions must be searched and generated (i.e., a diverging process of generating multiple solutions). Thirdly these different solutions must be compared and a selection or final combination must be made into a final solution (i.e., a converging process). The tools that can be used specifically in these different phases are described below.

2.1 Tools for analyzing affordances and ways to alter them

For the analysis of the affordances during the assembly process, the Typology table as described by Parmentier et al. [7] was offered to the students.

Table 1 Typology table, affordance analysis and constructing pathways, adapted from [7]

Affordance No.?	*Give the affordance a number*
Description	*Give a description of the affordance*
Level (manipulation / effect / use)	*manipulation / effect / use*
Type (AUA or AAA, see [18])	*AUA or AAA?*
Nested (Yes/No)	*Yes / No*
If nested, depending on affordance(s) No.? :	*affordance number(s)?*
Sequential (Yes/No)	*Yes / No*
If sequential, following on?	*affordance number(s)?*
Polarity of affordance?	*(+ / -)*
Current type (categorization according to Gaver [19])	*(FA,PA,HA)*
Desired type (categorization according to Gaver [19])	*(FA/PA/HA or CR)?*
Pathway to change between the types	*Physically (constraining) or Semantically?*
How?	*Which constraints, product semantics?*
Picture, product semantics	*Picture No.?*

They could use this table to first describe the affordance and secondly to define the typology of the affordance in line with the description. They could e.g. consider whether the affordance is desired (positive, e.g. the affordance of fixating a component correctly) or undesired (negative, e.g. the affordance of damaging the connection) or how it should be categorized according to the categorization of Gaver [19]. Gaver categorized affordances in Perceptible affordances (PA's, i.e., existing and perceptible action possibilities, e.g. when joining two components is perceptible and possible to the operator), Hidden affordances (HA's, i.e., existing but non perceptible action possibilities, e.g., when joining two components is possible but not clear to the operator), False affordances (FA's, i.e., perceptible but false, non-existing action possibilities, e.g. when joining seems possible to the operator but is not) and Correct Rejections (CR's, i.e., non-perceptible and non-existing action possibilities, e.g. when joining is not possible and not clear). The students could also consider whether they described the affordance as a potential interaction between an user and an artefact (artefact-user-affordance) or as an interaction between two artefacts (artefact-artefact-affordance), see [18]. When students use this table they are also triggered to consider whether the affordance itself or its perception should be changed. When a desired affordance (the polarity is positive) is hidden (HA according to the categorization of Gaver) one would want to change it in a desired perceptible affordance (+PA). In contrast when an undesired affordance (the polarity is negative) seems to be possible and perceptible (- PA), one would want to change it in a correct rejection (CR). As a consequence the Typology table (i.e., Table 1) not only helps to describe and define the affordance type but also triggers the students to consider whether to alter the affordance or its perception (especially in combination with the model in Fig.1 as it was described in [7]).

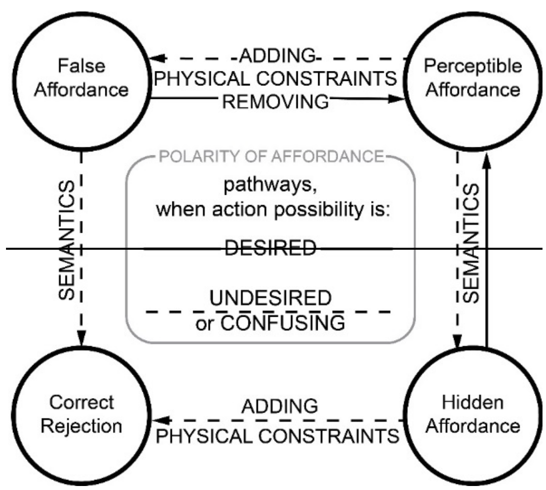


Fig. 1 Potential pathways, depending on polarity of affordance, to change the actual type of affordance. (adopted from [1] and initially adapted from [19])

As described by Parmentier et al. [1, p. 10] “Manual assembly can be considered a complex action in which multiple affordances, both AAA and AUA, follow each other in a sequential and nested structure.” Hence, when a problem is detected during the assembly it can be caused by one or multiple affordances that are possible (e.g. an undesired affordance that leads to an incorrect assembly), impossible (e.g., an impossible but desired affordance causing an assembly step that cannot be executed) or to an incorrect perception (e.g., an undesired affordance that is perceived as desired or a desired affordance that is not perceptible to the operator). Because an assembly step potentially exists out of many affordances (e.g. affordances between tools and the operator, between the operator and the component, between the components to be joined, between the tool and the component, etc.) it is important to describe the affordances and the associated difficulties as accurate as possible. Hence, it makes no sense to describe the affordance of assembly as such (e.g., the action possibility of assembling the components). It is important to describe the affordance much more precise: e.g. the action possibility of grasping the first component with a plier. However we argue that it is also important to consider this affordance from the two polarities, i.e., negative and positive. Hence we can describe the affordance as the action possibility of grasping the first component correctly with a plier and the action possibility of grasping the component incorrectly with a plier. This description from the two polarities is important because it triggers to consider solutions to firstly avoid undesired affordances (when described in the negative polarity) and secondly to consider solutions to make the desired affordance perceptible or possible, which will be explained further.

By considering and describing not only desired but also undesired action possibilities, different solutions for optimization can be found. Solutions can be thought of that make desired affordances possible (e.g. by removing constraints that prevented easy handling) and perceptible (e.g., by adding perceptual cues that trigger the operator to act upon that affordance). However, also solutions can be found to avoid undesired affordances (e.g. by adding constraints that make the undesired affordance impossible) or by removing perceptual cues that triggered the operator to act upon an undesired affordance (these are the pathways that were also illustrated in Fig. 1). Nevertheless, when an affordance is described as desired or as undesired, the pathways that are possible change (as illustrated in Fig.1). To really stimulate the students to generate solutions for every pathway (which, like discussed, depends on the polarity of the affordance) the pathways as illustrated in Fig.1 were separated in Fig. 2. The pathways that are possible when the affordance is desired were split from those that are possible when the affordance itself is undesired.

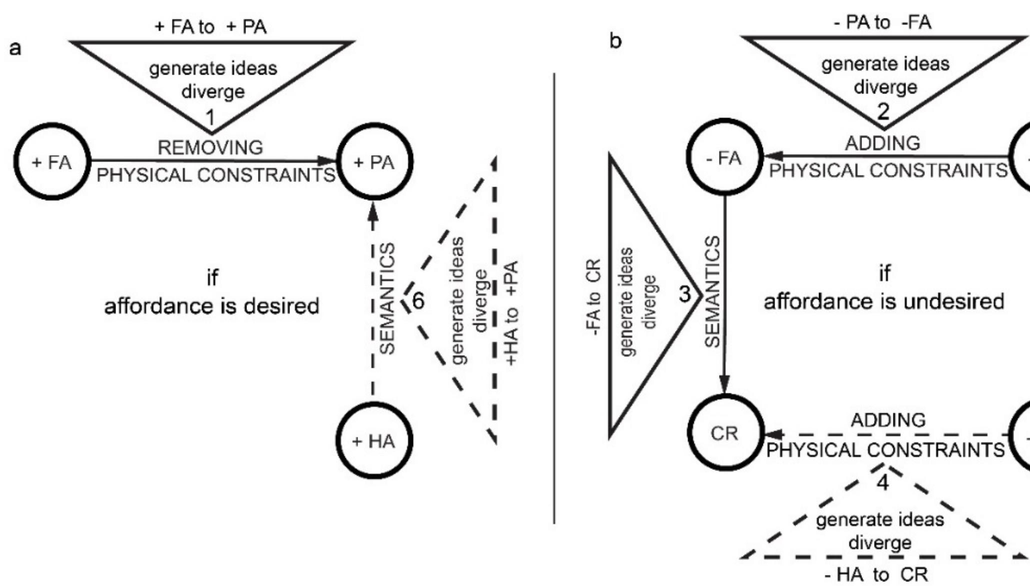


Fig. 2 searching multiple solutions (diverge) to alter the affordance or its perception for the desired (a) and undesired (b) affordance

The triangles in both parts (i.e. Fig. 2a and 2b) illustrate the diverging activity of generating ideas to make the necessary changes (i.e. to the perception of the affordance or to the affordance itself). In both parts of Fig. 2, different line types (i.e., continuous or dashed) illustrate the pathways that can be combined or not (similar line types can be combined). E.g., in Fig. 2a, you can start from a +FA or from a + HA, it makes no sense in combining these because the affordance in relation to the interacting operator is one type or the other, it cannot be both at the same time (e.g., it is perceptible to the operator or it is not perceptible, it cannot be both). All pathways and the associated diverging triangles also received a number, these numbers were also used in the linkage chart (i.e. in Fig. 3) which we use in the converging phase (i.e., to filter, select and combine solutions).

2.2 DFAM tools for filtering, selecting and combining solutions into a final solution

The main goal of the linkage chart (Fig. 3) is to firstly help comparing the solutions that were found when considering the individual pathways (as illustrated in Fig. 2) with each other on their impact for DFAM. Secondly the linkage chart aims to help the students with the selection or combination of "individual pathway solutions" into 1 final solution. To achieve this, it is important to first trigger the students to consider the differences between individual solutions on the level of DFAM (e.g., one solution can have an impact on multiple pathways while another solution only impacts one pathway). For example: it could be that by adding perceptual cues that trigger the perception of a desired affordance (i.e., pathway No. 6 in Fig. 2, changing a + HA into a +PA) also the perception of the undesired affordance is changed (i.e., changing a –PA into a –HA) by the mechanism of affordance threshold and the competitiveness of affordance perception (see the work of Lu and Cheng [20]). Secondly, it is important to trigger them to consider how they can combine the solutions they found (e.g., combining a solution that was found to change a –PA into a –HA with a solution that was found to change a +HA into a +PA) into one final solution.

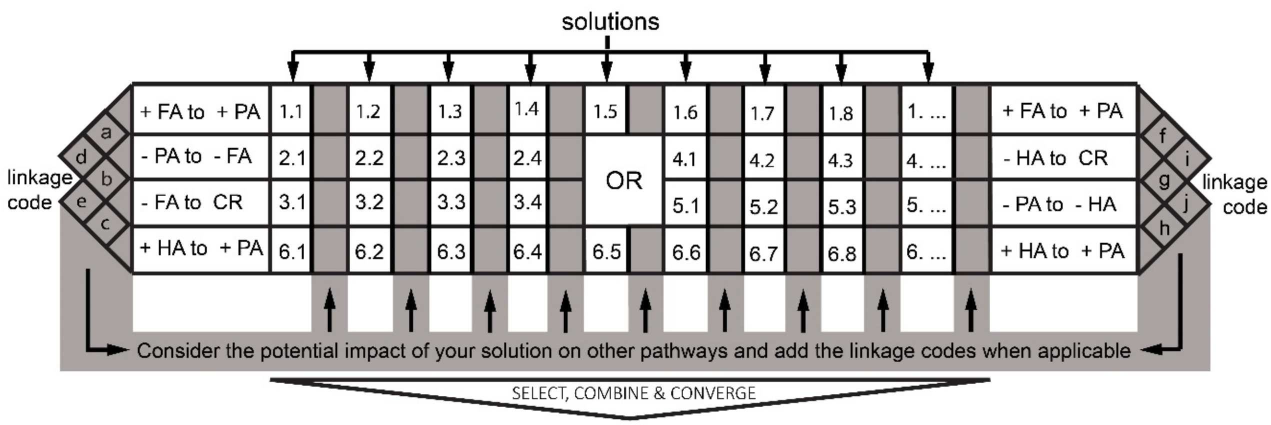


Fig. 3 Linkage Chart: compare, select and combine individual solutions (to alter affordances or their perception over a single pathway) into a final solution

The linkage codes as mentioned in Fig. 3 (i.e. the letter codes: a, b, etc.) are only mentioned to trigger the students to consider the potential impact of a solution (that was found when considering one pathway) on other pathways. For example, a solution that was found to change a +FA into a +PA (e.g., solution 1.1) can potentially have an impact on other pathways (e.g. on: -PA to -FA, -FA to CR, -HA to CR and -PA to -HA). We can see this in the Fig. 3 by means of the linkage codes [i.e., the linkage codes: 'a', 'd', 'f' and 'i' because these codes make the link between +FA to +PA and the other rows in Fig. 3]. It is of course a potential impact, meaning that some solutions will only impact the pathway for which the solution was initially found. It is up to the designer to consider the potential impact of a solution on other pathways. Some solutions will have more impact than others, so that one solution can have more potential than other solutions (i.e., on the level of making the assembly step more intuitive). However, this is of course not the only criterion to select or combine solutions, as impact on cost, production technique or context of use are also important.

3. Method

In this paper we discuss the method implementing DFAM in a project based learning course with design engineering students. During the project, the students redesigned existing products with a focus on DFAM after having analyzed the assembly process in the company.

3.1 Course and student description

The course took place in the second semester of the third year from the Bachelor of Science (BSc) program in Industrial Design Engineering Technology from the university where this study took place. Twentyeight students (19 male and 9 female) received 24 hours of lectures during a total of 12 weeks. The rest of the 180 hours were mainly spent on the project in which they had to redesign a product with the DFAM-approach.

3.2 Design task

The students had to redesign a light fixture in such a way that the assembly process would become more intuitive for the operator and lower the use of procedural instructions. The students were asked to consider the different assembly sequences, subassemblies, components, connections, jigs and fixtures and the environment. They had the liberty to change materials, shapes, colors, finishing's, of components and subassemblies. The final look when assembled and the performance of the initial product could not be changed however. The students also had to consider production costs because these could not raise dramatically.

3.3 Company and Product descriptions

In PBL emphasis is set on the resemblance of the design activities with real design activities and within real engineering settings (see, [8-10]). Selection of a company and selection of products to work on is therefore very important. When focusing on DFAM, designers want to design products that support the assembler in constructing an appropriate mental model of the assembly process. As a consequence, a company where manual assembly is used to assemble a wide variety of products was needed. Companies that work project based or companies that have a vast amount of different products or product families use in many cases manual assembly for its flexibility. However, manual assembly is not the only criterion to select a company and products for this case study. Students have to be able to redesign and prototype the product and test the assembly process. When a product is difficult to handle (e.g., due to its size) or when specialized tools are needed, prototyping and testing becomes difficult or even impossible for students. Nevertheless, a certain complexity is also desired because when the products are too easy to assemble (e.g., due to a limited amount of components or assembly steps) the focus on DFAM and the framework itself becomes less relevant in the project.

Eventually, Delta Light, an international and trendsetting company in architectural lighting products for both interior and exterior lighting was selected. The company designs, prototypes, assembles and tests its products in-house. In consultation with the lecturers of the course, 6 different light fixtures were chosen by the company to redesign them with a focus on DFAM. The products and the assembly of the products differed significantly from one another due to the difference in components, number of components, assembly steps, use of jigs and fixtures, etc. The assemblies were all challenging enough (i.e., they had enough components, assembly steps and opportunities for redesign with a focus on DFAM). The selected lightfixtures are shown in Fig. 4. Information on these lightfixtures is provided in Table 2 to give an indication of the level of complexity.

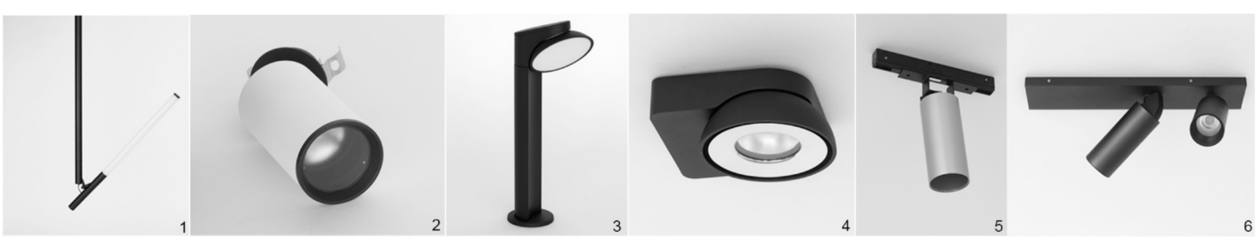


Fig. 4 Products of Delta Light that were selected to apply the DFAM framework

Table 2 Comparison of the products, indicating general complexity of the products and the assembly process

Product	No. of components	No. of unique components	Documented instruction steps
1	66	44	216
2	31	22	72
3	42	28	120
4	48	32	140
5	33	25	121
6	72	34	138

3.4 Procedure

To improve existing products on the level of assembly meaning, several well-documented design iterations [iterations of generating ideas (diverging), selecting and combining ideas (converging), prototyping and testing ideas (validating)] need to be completed during a redesign project. During the course, the students went through three different phases of which two phases were individual (i.e., the analysis phase and an individual redesign phase) and one in group (the final redesign phase was in group). These phases are also illustrated in Fig. 5 on a timeline which summarizes the course of the project.

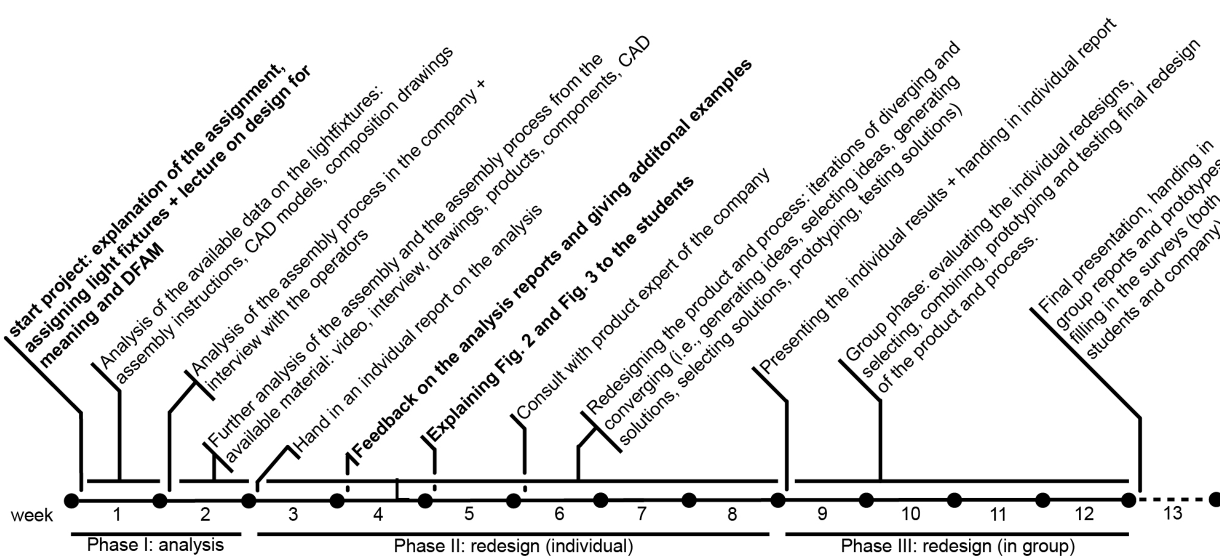


Fig. 5 Timeline of the project within the course (lecturer input in bold)

The students were randomly assigned to one of the 6 light fixtures. The company provided all documentation on the selected light fixtures (i.e., CAD models, exploded views, bill of materials and assembly instructions) so the students could prepare themselves for the second week. The company also provided two light fixtures of every type (i.e., an assembled and a disassembled version). In the second week the students visited the company and could follow the assembly of the light fixture assigned to them. The assembly process was filmed and the students took notes during the assembly of the product and could ask questions to the operator after completing the assembly. Every student had to analyze the assembly process to identify difficulties, problems, etc. on both a physical and cognitive level. The students were asked to clearly describe the difficulties on an affordance level, state the polarity of the affordance (whether an affordance is positive or negative, see Gibson [21]) and use the classification according to Gaver [19] (i.e., in PA's, HA's, FA's and CR's). The students could use the Typology Table (i.e., Table 1) in relation to Fig. 1 for this (e.g., a desired affordance is not clear to the operator: +HA, an undesired action is feasible and perceptible: -PA, the assembly step is hard to execute e.g., meaning that the operator has to try multiple times before being successful: i.e., a +FA when the attempt fails). To apply the latter, the students received a lecture on DFAM [1] and design for meaning, referring to affordances ([18, 19, 22, 23], product semantics [24], constraints and conventions

[23]). The students had to hand in a report of their analysis in the third week. After analysis of these first reports by the lecturers, it came forward that some students had difficulties to analyze and describe the affordances correctly. Errors in defining the polarity in relation to the description of the affordance, or the level on which the affordance was described (see the descriptions-of-affordances-model of Pols [25]) were common. Feedback on these errors (i.e., additional examples of how to describe and categorize the affordances) was given to the students in week 4.

For the second phase, the students started redesigning the product or the process with a focus on DFAM. Specifically, the students considered how to change affordances (e.g. of components, subassemblies in relation to jig, fixtures and tools) or their perception to optimize intuitive assembly. In week 5 of the assignment the students received the model in Fig. 2. This model aims to trigger them to search multiple solutions (diverging process) for every pathway (i.e., the pathways they need to alter the affordance or its perception) and for both desired and undesired affordances. They also received the linkage chart in Fig. 3 to help them compare, combine and understand the potential interrelated effects of solutions. In week 6, they could book a consult with a product expert of the company who would answer specific questions on the existing light fixtures. Since the company is an important stakeholder in the redesign of the product, it was important to understand past design choices, production details, costs, etc. in order to compare different solutions. The students continued redesigning the product and/or the process with a focus on DFAM and were prototyping and testing their solutions until week 9 of the assignment where they had to present their solutions and prototypes and hand in an individual report.

After this individual deadline, the students who had been working on the same light fixtures started working in group (6 groups were formed). This final stage was important to let the students learn from each other. They also had to reconsider their personal ideas and decide which solution was best for the product, which is important when working in group. It is not about putting your own idea forward but considering with an open mind what the best solution is. In this final stage of the project, every group had to come to a consensus to make one redesign of the product and or process with a focus on DFAM. As a consequence they had to evaluate, compare, select and combine their individual solutions or use them as an input for a new design (to be a finalized in week 13). Following the groups also reported on the different potential solutions they came up with and secondly gave arguments to support their final solution (a selection or combination of the potential solutions identified.) Finally the results were presented to a jury with members of the company in week 13. A report, final prototypes and drawings were also handed in. Both the students and members of the company were asked to fill in a survey in week 13. The students were asked questions on the added value, the applicability, etc. of the DFAM framework and the different tools. The survey was constructed out of nineteen statements (see Table 4) accompanied with a five-point Likert scale and space to add comments. There were also two open questions offering the students to freely give their opinion on the practicality of different tools and aspects of DFAM. To allow the students to give their own opinion and to avoid social desirability bias, the survey was taken anonymously.

After reception of the reports, the descriptions of the affordances and the pathways identified and used by the students to alter the affordances or the perception were evaluated. When, during evaluation of the reports, it was found that the pathway reported did not match the description or the action taken on the affordance, this was corrected after a double check by another evaluator. If this was not entirely clear due to an inadequate or missing description of the affordance, the pathway was registered as it was.

4 Results

4.1 Product or process changes presented by the groups

Different solutions to alter an affordance can have a different impact on the initial affordance, some change the affordance itself while other solutions only impact the perception. Nevertheless these changes can all be linked to the pathways described in Fig. 1. However, some groups also described a pathway directly from a - PA to a CR which is in fact a combination of two pathways (i.e., –PA to –FA to CR or –PA to –HA to CR). When a pathway like this was mentioned by the students, this was registered as two different pathways from –PA to –FA and from –FA to CR. This combination was chosen over the other combination (i.e., from –PA to –HA and from –HA to CR) because the pathway from –PA to –FA was already much more reported by the teams compared to the pathway from -PA to -HA (i.e., initially in 87,76% and after this correction in 89,04% of the pathways starting from a -PA). Eventually 285 pathways that were reported in the team reports were taken into account and registered.

In Fig. 6, we have illustrated the distribution of the pathways (linked to the solutions) presented in the final team reports. The distribution of the pathways that were first reported to find solutions (all potential solutions) and secondly those that were used in the final solution are both illustrated in Fig. 6 (i.e., for all potential solutions in Fig. 6a and for the final solutions in Fig. 6b). Finally in Fig. 6c the distribution of the real effect of the final solutions on the different pathways is illustrated. This differs from the pathways used in the final solutions (Fig. 6b) because a solution can have a bigger effect than only the pathway for which it was considered (e.g., a solution can have an impact on the affordance itself, its perception or even on another affordance). This impact was not explicitly reported by the students but could be identified when evaluating the reports (a subset was also independently double checked by another evaluator).

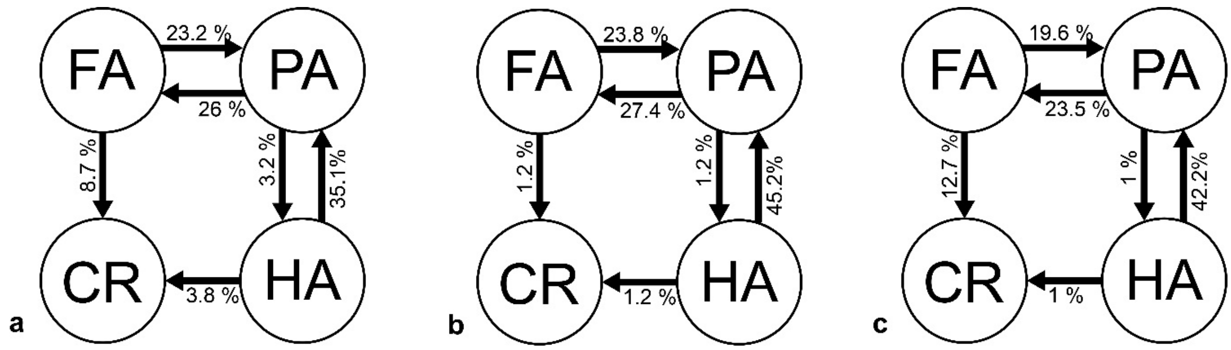


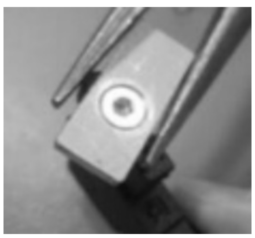
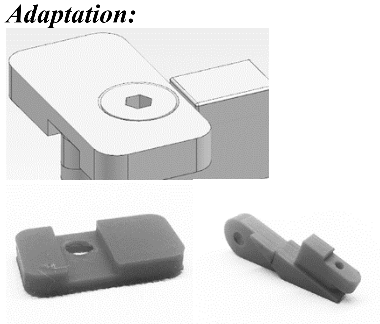
Fig. 6: **a** distribution of pathways being considered by the teams **b** distribution of pathways being used by the teams in their final solution **c** distribution of the effects of the final solutions on the pathways (based on the final reports of teams)

In Fig. 6 we can see that changing +HA's into +PA's is most common (i.e., 35.1%, 45.2% and 42.2%), followed by changing -PA's into -FA's (i.e., 26%, 27.4% and 23.5%), +FA's into +PA's (i.e., 23.2%, 23.8% and 19.6%), -FA's into CR's (i.e., 8.7%, 1.2% and 12.7%), -HA's into CR's (i.e., 3.8%, 1.2% and 1%) and -PA's into -HA's (i.e., 3.2%, 1.2% and 1%). This is interesting because it illustrates that the problems encountered by the teams mostly relate to desired affordances not being clear to the operator (i.e., +HA's that need to be changed into +PA's). This is also in line with the results that were presented in [7] where students designed products with a focus on design for meaning in the use context (facilitating and promoting perception of the intended use, and preventing incorrect usage) Pathways that are taken when a desired affordance is not perceptible (i.e., +HA's to +PA's) or not feasible (i.e., +FA's to +PA's) represent 58.3 % (in Fig. 6a) but already 69% (in Fig.6b for the final solution) of all the pathways that were needed to improve the assembly process. So a majority of the actions are linked to intended affordances that are not perceivable or feasible for the user. The remaining percentages are linked to undesired affordances. Another categorization can be made for the type of changes (adding or removing constraints to change the affordance itself or semantic changes to make the affordance perceptible or to hide it). Nearly half of the changes are semantic changes (i.e., 47% in Fig. 6a and 47.6% in Fig. 6b). There is however a clear difference when looking at these semantic changes. In Fig. 6b, 45.2% which is 95% of all semantic changes here, involve solutions that change a +HA into a +PA. In Fig. 6a, this is 35.1% which is only 74.7% of the semantic changes. When looking at the pathways that are being used in the final solutions to change affordances or their perception (i.e., in Fig. 6b), we can see that 52.4% of the solutions change the affordance itself and 47.6% use semantics to change its perception. So a slight majority of the final solutions proposed by the teams focus on changing the affordance itself by adding or removing constraints. However, when we look at the total impact of these solutions on the pathways (i.e., in Fig. 6c) we can see that the impact on the semantic axis (i.e., changing perception) has increased to 55.9% (i.e., 12.7+1+42.2). This illustrates that solutions that initially were found to change the affordance itself (e.g., make a desired affordance feasible or make an undesired affordance impossible) also impact the perception (semantics). For example, by adding constraints that made an undesired affordance impossible it also became perceptible that this affordance was undesired. The addition of constraints also had a semantical effect and illustrated that the affordance was indeed not possible and as a result, the –PA was not only changed in a –FA but also in a CR. Following, these results show that most teams considered different pathways to alter the affordances or their perception and that some solutions impacted multiple pathways.

4.2 Considering pathways in different solutions spaces

After analysing the assembly process and prioritising the problems to be solved, all design teams proposed their solutions in a final report. The solutions that we present in Table 3 are only a small selection of solutions that were considered by the groups. The solutions that are presented are solutions that were selected by the groups as their final solutions for the problem identified (they considered many more alternatives). The selection was made to give examples of solutions in different solution spaces (i.e., firstly the product, secondly the tools, jig and fixtures, thirdly the environment and finally the process itself). In Table 3 we also discuss how these solutions are linked to the pathways and how they solve the problems.

Table 3 Examples of solutions found by the teams during the project

<table>
<tr><td rowspan="2">1</td><td rowspan="2">Problem definition: It is unclear for the operator how to position and fixate the clamping plates correctly.
</td><td colspan="2">Pathways: +HA to +PA: make the desired position clear
-PA to –FA: make incorrect positioning impossible</td><td>Solution space: Product</td></tr>
<tr><td>Adaptation:
</td><td colspan="2">Solutions: +HA to +PA: the chamfer on the hole indicates the side to insert the screw. The slot and the asymmetric position has a semantic function because it links the contact surfaces and positions to one-another.
–PA to –FA: the chamfered hole, the slot and the asymmetric position of the hole also have a constraining function, it becomes impossible to assemble the plate incorrectly.</td></tr>
<tr><td rowspan="2">2</td><td colspan="2">Problem definition: Tightening the trumpet nipple in the plate is a difficult manipulation where the operator has to use both tongs and wrench while holding the nipple. The positioning of the tongs is not so easy. The grounding that is going through the nipple can also be damaged by the tongs.
</td><td>Pathways: +FA to +PA: make it possible to assemble this correctly by removing the constraints that limit the operator in holding the plate firmly with the thongs (small surface to apply the tongs).

-HA to CR: make it impossible to damage the grounding by adding constraints that prevent the use of the tongs</td><td>Solution space: Tools, Jigs & Fixtures</td></tr>
<tr><td colspan="2">Adaptation:
</td><td colspan="2">Solutions: +FA to +PA: the limitations (constraints) that prevented the operator from holding the plate properly (small contact area on the edge of the plate) are removed by using a Jig. The plate is properly held by the Jig without the need to use the tongs.

-HA to CR: Damaging the grounding (undesired hidden affordance) is made impossible by applying the jig (adding constraints). Any tongs can no longer damage the cable because the jig is in its way. Moreover, by using the jig you no longer need the tongs.</td></tr>
<tr><td rowspan="2">3</td><td colspan="2">Problem definition: The operator experiences difficulties to find the appropriate parts in the different assembly steps.</td><td>+HA to +PA: link the different parts more clearly to different assembly steps so it is easier to locate them.</td><td>Solution space: Environment</td></tr>
<tr><td colspan="2">Adaptation:</td><td colspan="2">Solution: The subassemblies all received a different color in the instruction. A box was designed to hold the</td></tr>
</table>

	 	different components and colors matching the different subassemblies were added. This made it easier for the operator to find the desired component.	
4	***Problem definition:*** the operator is experiencing many difficulties to insert a lens correctly in a housing. (fixate it with another component which is already in the housing)	***Pathway:*** +FA to +PA: remove the constraints that prevent easy insertion of the lens.	***Solution space:*** Process
	Adaptation and solution: The assembly sequence was changed. The lens is now first joined with the component (i.e., a new subassembly). The subassembly is then easily being installed in the housing.		

3.1 Students evaluating the framework, results of the survey.

The aim of the survey was to gather insights on how the framework was evaluated and used by the students. In Table 4 we share the answers on the statements by showing the mean values and the standard deviations of the 27 student responses. Additional comments (when available) that were not open to interpretation and that represented the mean and outliners (selected on this basis to give an overview) were reported in Table 4. The answers on these statements were interpreted qualitatively due to the limited number of respondents (only 27 students). The survey was taken anonymously to avoid social desirability bias. The comments were all translated from Dutch.

Table 4 Results of the survey: answers and comments of the students on the statements

	STATEMENTS (translated from the original statements in Dutch)	*M*	SCALE LABEL	*SD*	G
1	**Explicitly considering affordances and product semantics of the different assembly steps offered a better insight when analysing the assembly process.**	**3.81**	3 = neutral 4 = agree	0.921	A
	3C1/3: It was confusing in the beginning. We had to put more focus on this than on the problem. It was very practical to describe the problem. 7C1/4: In the beginning it caused some frustration, but once I got it right, the underlying problems became clear to me.				
2	**Explicitly considering affordances and product semantics of the different assembly steps offered a better insight when searching for solutions.**	**4.07**	4 = agree 5 = totally agree	0.730	A
	3C2/4: It forces you to consider the problem from different angles which results in multiple solutions that can be found. 7C2/4: In the beginning it caused some frustration, but once I got it right, the underlying problems became clear to me. It helped especially iterating and generating solutions (constraints and semantics) 10C2/3: It gave a good insight, but sometimes it felt a bit restricting 17C2/4: You can search more specifically for solutions 18C2/5: it is easier to look for solutions if you have specific techniques to use: semantics, physical constraints				
3	**Considering the desired affordances during the different assembly steps was already sufficient, it is not necessary to consider undesired affordances to achieve an intuitive assembly process.**	**2.15**	2 = disagree 3 = neutral	0.770	B
	3C3/1 It is just interesting to look at the problem from different angles. 10C3/2: It is a combination of both, after all you never know how another person sees everything.				
4	**Considering undesired affordances is not necessary to avoid problems during assembly.**	**2.26**	2 = disagree 3 = neutral	1.163	B
5	**Describing the desired affordances in the different assembly steps was easy.**	**3.30**	3 = neutral 4 = agree	0.912	C
	6C5/3: It depends on the type of affordance				

6	**Describing the undesired affordances in the different assembly steps was difficult.**	**3.04**	3 = neutral 3 = agree	1.055	C
	2C6/3: It was less difficult than describing the desired affordance, it is easier to explain why something goes difficult rather than to explain why something goes well.				
7	**Approaching the assembly problem from the desired affordance and identifying it as a + PA, +HA or +FA is important to gain insight.**	**3.89**	3 = neutral 4 = agree	0.698	B
	11C7/3: I found it complex to work with positive and negative affordances 22C7/2: it can help to find solutions, but the most logical ideas have not been found with the help of this				
8	**Approaching the assembly problem from the undesired affordance and identifying it as a - PA, -HA or -FA is important to gain insight.**	**3.91**	3 = neutral 4 = agree	0.651	B
9	**I understand Fig 1 (i.e., in this paper)**	**4.41**	4 = agree 5 = totally agree	0.572	D
	24C9/4: currently I understand this, in the beginning this was confusing, the arrows were not entirely clear 25C9/4: I sometimes had the impression that the arrow “removing physical constraints” had to be “adding physical constraints” 27C9/4: Fig 1 has helped me multiple times for searching solutions by following the arrows towards a desired affordance type.				
10	**I find Fig 1 (i.e., the figure number in this paper) not useful at all for identifying the problem in the assembly step and suggesting a possible solution.**	**2.11**	2 = disagree 3 = neutral	0.847	E
	2C10/3: Not immediately because at first I did not understand Fig. 1 *12C10/4:Using it reverse is much easier* *13C10/2: It helped me sufficiently* *27C10/2 It was not always useful, it sometimes limited creativity*				
11	**I understand Fig. 2 (i.e., the figure number in this paper, to trigger the generation of ideas when considering both desired and undesired affordances)**	**4.22**	4 = agree 5 = totally agree	0.506	D
	11C11/3: Fig. 1 is easier to use 14C11/5: the division of the scheme is clear to understand				
12	**I find Fig. 2 very valuable to stimulate me to think about different solutions to change the affordance or its perception**	**3.30**	3 = neutral 4 = agree	0.912	E
	9C12/2: it also limits you: if you describe the issue in one way, you usually only have 1 possible path 14C12/4: it is good to encourage you to consider different pathways				
13	**Fig. 2 is very valuable in combination with the table (i.e. Fig. 3 in this paper) to find an ideal solution with a focus on design for assembly meaning**	**2.93**	2 = disagree 3 = neutral	0.874	E
	1C13/2: I was not able to find combinations on the basis of the table (i.e., Fig. 3 in this paper). 3C13/3: They are useful tools but they can also be very confusing. I would use them in the future as inspiration but would not focus too hard trying to do everything with them. 9C13/1: it does not explicitly take into account a change in tooling or instructions (and the ideal solution does not exist)				
14	**The table (in Fig. 3 in this paper) is not clear to me.**	**3.07**	3 = neutral 4 = agree	1.072	D
	3C14/4: There is too much and unclear information. It causes more confusion. 8C14/3: The table is fairly clear (apart from the separation between the two sides). The use is less intuitive. 24C14/2: the numbers are not clear to me 26C14/4: I do not completely understand how to assign the linkage codes				
15	**I find the table (in Fig. 3 in this paper) very valuable for generating, selecting and combining solutions and for**	**2.56**	2 = disagree 3 = neutral	0.892	E

	mapping the impact of the solutions themselves				
	3C15/1: It did not help and caused an extra workload, confusion and frustration 13C15/3: It is only practical to identify solutions that have an effect on multiple problems 14C15/3 The table is sometimes too complex and too small to describe the solutions. (illustrating solutions as 1, 2, 3 is also difficult)				
16	**I used the tools (diagrams and tables) provided methodically.**	**3.41**	3 = neutral 4 = agree	0.745	F
	8C16: I used Fig. 1 and Fig 2 combined with own intuition. I did not use or not explicitly used the linkage chart (Fig. 3). This could depend on the problems and the solutions. 9C16/1: I only used Fig. 2 18C16/4: The linkage chart (Fig. 3 in this paper) was not used systematically due to its complexity				
17	**I used the tools provided rather intuitively and not always to the letter**	**3.81**	3 = neutral 4 = agree	0.834	F
	3C17/4: I had to fill in some tables twice because I had used them incorrectly. 9C17/3: Fig. 2 was used was used methodically to know which pathways were applicable, Fig. 3 was only used intuitively. 18C17/3: Fig. 3 was used more intuitively				
18	**The framework was very helpful to identify the problems with the assembly**	**3.52**	3 = neutral 4 = agree	0.849	A
19	**The framework did not help me to find solutions to make the assembly more intuitive**	**2.48**	2 = disagree 3 = neutral	0.893	A
	11C19/2 I found that the framework (as far as I understood it) helped me to generate multiple solutions 14C19/2: sometimes this is time-consuming, but it does make links between solutions				
20	**Which method, scheme, table did you find very practical to use and has given you important insights during this assignment?**				
21	**Which aspect of DFAM did you find difficult to apply in practice or confusing, complex, etc. ?**				

It is important to reconsider the answers on the survey in relation to the 6 different groups in which the statements can be categorized (i.e., assessing the general value attributed by the students to the framework [A], the added value of considering both polarities of affordances [B], the ease of describing affordances [C], the understanding of the different tools [D], the perceived value of the tools [E], and the way the tools were used [F]). These groups are also mentioned in Table 4 in column G. In the following overview we will discuss for these categories how we can evaluate the answers on these statements by considering not only the means of the answers but also in relation to comments additionally made by students. A selection of these comments can be found in Table 4. In the following section, we use the same numbering as in Table 4 when referring to these comments.

The *added value of the framework [A]* was generally assessed by statements 1 and 18 *for the analysis of the assembly process* and by statements 2 and 19 *for identifying solutions*. The mean values of the answers of the students on statement 1 (M=3.81) and statement 18 (M=3.52) illustrate that a majority of the students (i.e., 74.07% on statement 1 and 66.67% on statement 18) agree or totally agree that considering affordances and product semantics offered better insights when analyzing the assembly process (assessed by statement 1) and was helpful to identify the problems with the assembly (assessed by statement 18). The mean values of the answers of the students on statement 2 (M=4.07) and statement 19 (M=2.48) show a difference. However, the wording in statement 19 was reversed. Following, the answers on these statements are more or less in line. A majority of the students (i.e., 85.19% on statement 2 and 66.67% on statement 19) agrees with statement 2 and disagrees with statement 19 showing again a more positive evaluation toward the value of the framework for identifying solutions [i.e., for offering insights when searching for solutions (assessed by statement 2) and for helping to find solutions (assessed by statement 19)]. In general, these results show a positive evaluation by a majority of the students towards the added value of the framework.

Statements 9, 11 and 14 assess the perception of the students of their *own understanding of the tools [D]* offered to them (i.e., the tools illustrated in Fig.1, Fig.2 and Fig.3 of this paper).
As illustrated in Table 4, the means of the answers on statements 9 and 11 (i.e., 4.41 and 4.22) are between agree and totally agree. These values indicate that a big majority of the students (i.e., 96.30% on both statements) believe to understand the tools that are illustrated in Fig.1 and Fig.2. However, the mean value of the answers on statement 14

(i.e., 3.07, which is closest to neutral) illustrates that the Linkage Chart (i.e., Fig 3 in this paper) is considered more difficult to understand. These results show a positive evaluation by a majority of the students towards the understanding of Fig. 1 and Fig. 2 but a more neutral evaluation towards the understanding of the Linkage Chart (i.e., Fig. 3).

When evaluating the answers of the students on the statements that assess the *value attribution to the tools [E]*, we see some clear differences between the different tools. The mean value of the answers on statement 10 (i.e., 2.11) illustrates that a big majority of the students (i.e., 81.48%) more or less disagrees with statement 10 and more or less agrees that the basic model as illustrated in Fig.1 is considered useful to identify problems and to suggest solutions. The adapted version of this basic model (i.e., Fig. 2 in this paper) shows more neutral (i.e., a mean of 3.30 on statement 12 and a mean of 2.93 on statement 13) results. Also, the mean value of the answers on statement 15 (i.e., 2.56, which is between disagree and neutral) indicates that a majority of the students do not consider the Linkage Chart (Fig.3) very valuable for generating, selecting, combining solutions and for mapping the impact of the solutions. Following, the students responded more or less positive on the model in Fig.1 (e.g., statement 10), more or less neutral on the model in Fig.2 (e.g., statements 12 and 13) and between neutral and negative on the table in Fig.3 (e.g., statement 15). Additional comments of the students on these statements give some more insights on these results. Some comments indicate the complexity of using (e.g. comments 14C15/3, 12C10/4), the sometimes limited understanding of the tools (e.g., Comment 2C10/3) or even the restricting nature of the tools compared to following ones intuition or creativity (e.g. comments 27C10/2 and 9C12/2).

The mean values of the answers of the students on both statements addressing *the way they used the tools [F],* i.e., methodically (statement 16) or rather intuitively (statement 17) are between neutral and agreement (i.e., 3.41 for statement 16 and 3.81 for statement 17). On statement 16 (addressing whether they used the tools methodically) 40.74% responded neutral and 51.85% agreed while on statement 17 (addressing whether they used the tools rather intuitively) 70.37% agreed or totally agreed. This gives a somewhat divided picture. However when looking at the comments of the students on these statements we can see some differences between the different tools. As a consequence some tools are used more methodically and others more intuitively. The number of participants responding on these comments (only 9 additional comments on these two statements in total) is however too low to draw any clear conclusions from for specific tools.

Statements 3, 4, 7 and 8 evaluate *the perceived importance of considering both polarities [B]* of affordances (i.e., desired and undesired, e.g. correct positioning of a component versus incorrect positioning of a component). The means of the answers on statements 3 (i.e., 2.15) and 4 (i.e., 2.26) are both close to a disagreement on these statements (77.78% on statement 3 and 70.37% on statement 4 disagreed or totally disagreed). However, the wording in these statements was reversed, illustrating that the students more or less agree that considering undesired affordance is valuable to achieve an intuitive assembly process and to avoid problems during assembly. These results are also in line with the mean values of the answers on statement 7 and 8 (statements that explicitly address the analysis of the assembly problem from the two polarities). Here again, the mean values on these statements (i.e., 3.89 for statement 7 and 3.91 for statement 8) and the number of agreements or total agreements (i.e., 70.37% on statement 7 and 74.07% on statement 8) indicate that the students more or less agree that both approaches (i.e., from both desired and undesired affordances) and explicitly identifying them as +PA's, +HA's, +FA's, -PA's, - HA's and -FA's is important to gain insights. The latter is also supported by some of the comments of the students (e.g., 3C3/1: "It is just interesting to look at the problem from different angles." and 10C3/2: "It is a combination of both, after all you never know how another person sees everything.") Another comment that answered more neutral on statement 7 (i.e., comment 11C7/3) also indicates the complexity of considering both polarities. This is also linked to the description of the affordance because the description of the affordance should be in line with the type of the affordance. In sum, the results show that considering both polarities of affordances is perceived important by a majority of the students.

Ease of describing [C] both desired and undesired affordances was addressed with statements 5 and 6. The means of these answers (i.e., 3.30 on statement 5 and 3.04 on statement 6) are both between neutral and agreement but closer to neutral when considering the ease of describing affordances. Following, students find it not difficult but also not easy to describe desired or undesired affordances.

Besides answering on the statements, the students were also asked to answer on two open questions (i.e., question 20 and 21). Question 20 assessed which method, scheme or table they found very practical to use and has given them important insights during the assignment. In contrast question 21 assessed which aspect of DFAM they found difficult to apply in practice, confusing, complex, etc. The answers on these open questions offered some very interesting insights. Referring to the answers on question 20, Fig. 1 and Fig. 2 were mentioned most (i.e., Fig. 1 by 59.26% of the students and Fig. 2 by 44.45% of the students) as the most practical to use and offering important insights during the assignment. The typology table (i.e., Table 1) was also mentioned by 18.52% of the students while the linkage chart (i.e., Fig. 3) was mentioned only once (i.e. 3.70% of the students). This result for the linkage chart is also reflected in the answers on question 21. The linkage chart (Fig. 3) is mentioned by 51.85 % of the students as the most difficult, confusing or complex. Also describing, defining and identifying affordances is considered complex, this was reported by 18.51% of the students. Other comments on these questions also illustrate the differences between the students. One student commented he or she found none of the tools practical or offering interesting insights while other comments clearly illustrated appreciation for the tools “interesting to identify problems objectively” or that Fig.1 and Fig.2 are “practical for exploration” or “very interesting”.

4 Discussion and limitations

An interview study of Boess (2008) showed that many designers rely on their intuition when considering meaning in product use. In this interview study of Boess, these designers did not know the applicable theories or found them too theoretical. They preferred concreteness rather than abstracted descriptions and as a consequence relied on their intuition.
In this case study on DFAM, we also started with explaining DFAM more theoretically (i.e., by explaining affordances and product semantics and by referring to the framework presented in [1]). Nevertheless, besides giving the students only a theoretical explanation on DFAM, we also offered them a clear methodology and tools to use in different phases of the design or redesign process. We asked the students to really use these tools in their design project. The results in Table 3 illustrate that the students found interesting solutions to improve the intuitiveness of the assembly process (i.e., by making undesired action possibilities impossible or imperceptible and by facilitating and highlighting desired action possibilities) and this not only on a component and subassembly level but also on the level of tools, jigs and fixtures, the environment and the process itself. The results were also positively evaluated by the company, who stated that the results were relevant and mostly useful, also because the students took existing preconditions (e.g., moulds that were already ordered, etc.) into account. These results illustrate that the students were capable of finding valuable solutions when focusing on DFAM. The project-based learning context (real products, analysis in a real company), the consultations with the mentors and with the company and the final group phase all suggests their value to learn to design for meaning in assembly. The question remains however whether the framework and the tools helped them to design for assembly meaning and how it was perceived.

The survey was used to gather these insights, resulting in some interesting findings. A majority of the students agreed that considering affordances and product semantics explicitly offers important insights when analyzing the assembly process (statement 1, on which 74.07% of the students agree or totally agree) and searching for solutions (statement 2, on which 85.19% of the students agree or totally agree). Moreover, a majority of students also considered the framework to be very helpful to identify the problems with the assembly (statement 18, on which 66.67% of the students agree or totally agree) and to find solutions to make the assembly more intuitive (statement 19, on which 66.67% disagreed or totally disagreed with the statement and thus more or less agree that it was helpful to find solutions). These are important findings because it shows the value of the framework in the different phases of the (re)design process with a focus on DFAM (i.e., phases of analyzing and identifying the problems and opportunities and broadening the perspective, exploring multiple ways to find solutions and phases of converging and moving towards a solution). Nevertheless, although all these evaluations are positive towards the framework, the results of the survey indicate that the framework is valued more for offering insights during analysis of the assembly process (assessed by statement 1) and when searching for solutions (assessed by statement 2) than for identifying the problems (assessed by statement 18) and finding solutions (assessed by statement 19). Following, it is valued more for offering valuable insights. To understand this better it is important to consider the work of a designer and the feedback students gave on the tools.

The tools that were offered all have a specific purpose as discussed earlier in this paper. First the typology table (i.e., Table 1) in combination with Fig.1 is used for the identification and analysis of the affordances and to identify potential pathways to alter them. Following these tools are used in the first phase of DFAM in which the assembly process is analyzed and potential problems or difficulties are identified. The framework was evaluated to be valuable

in this phase, this is also confirmed by the clear preference of the students for Fig. 1 over the other tools when being asked to identify the tools that were considered most practical to use and offering important insights. This is also supported by the answers from the students on statement 10 (see, the statements in Table 4). Second, Fig. 2 is used for searching multiple solutions (diverging process) to alter the affordances or their perception starting from the different pathways. This model is clearly used to stimulate the designers to consider the problem from different angles (desired and undesired affordances) and to search multiple solutions. Fig. 2 was also mentioned 12 times (out of 27 students) as very practical and offering important insights during the assignment when asking this question during the survey. This is also in line with the clear value attributed to the framework by the students for broadening the perspective and exploring multiple ways to find solutions (the focus of Fig. 2). Third, Fig.3 was offered to the students as a tool to filter, select and combine solutions into a final solution. This tool was however mentioned 14 times as the most difficult to apply in practice, confusing or complex. It is clear from the answers of the students that they had difficulties using this tool, some also clearly indicated that they were not capable of using this tool because they did not understand it.
This is also potentially related to the fact that you cannot use the tool in the format it is presented. It is rather an illustration of how solutions found by considering one pathway can impact other pathways or could be combined with other solutions. You cannot just write down your solutions in this Fig. 3, you have to do it separately from this Fig. 3. The lack of understanding on how to use this can potentially have been an important factor that could explain why students valued the framework less for helping to find solutions (only 66.67% of the student disagreed or totally disagreed on statement 19 and thus agreed or totally agreed on finding it helpful to find solutions to make the assembly more intuitive). Nevertheless, also 18.5% responded more neutral, and 15% (i.e., 4 out of the 27 respondents) did not find the framework useful on this point. However, it is also clear that the framework cannot find the solutions for the designer, this is still the task of the designer. The tools only offer the designer a method for analysis, exploration of solutions from different perspectives and a method for selection and combining.

These results highlight again the duality of using a method and tools in a design process. Some students really value the framework and the tools which is illustrated by the comments: 3C2/4 “It forces you to consider the problem from different angles which results in multiple solutions that can be found.”, 7C2/4 “In the beginning it caused some frustration, but once I got it right, the underlying problems became clear to me. It helped especially iterating and generating solutions (constraints and semantics)”, 17C2/4 “You can search more specifically for solutions” and 18C2/5 “it is easier to look for solutions if you have specific techniques to use: semantics, physical constraints”, 14C12/4 it is good to encourage you to consider different pathways).
Others find it a bit restricting (see comments 10C2/3, 9C12/2 in Table 4) or limiting creativity (e.g., comment 27C10/2 in Table 4).

Limitations here were the rather small group size of 28 students (27 respondents on the survey) from one university and one education program, the individual differences (personality, competencies, etc.), the difference between the products and the creativity of the design process. This makes it difficult to generalize the results. Due to the timeframe, time to practice with the tools was also limited, this was clearly another limitation because it impacted for some students the understanding of the tools as commented by some (e.g., comment 3C1/3, 7C1/4). It was also the first time for the teachers to offer these tools to design for assembly meaning to the students. As a consequence, experience was lacking to prevent some of the difficulties that were experienced by the students when working with these tools. This was another limitation that could have impacted the results.

It is clear that the results of the survey showed some mixed results with some students really valuing the framework and the tools offered to them while others consider them too restricting, limiting creativity or complex to use. This difference in value attribution is potentially also linked to the design task itself. The tools are meant to help the designer in different phases of the process, they however do not generate the solutions. It is still up to the designer to generate the solutions. It is clear that some designers would use the tools while others prefer to work more intuitively. These results again illustrated the duality and complexity of using tools in a creative design process and the individual differences between students (i.e., future designers). These results show that the tools are certainly valuable for a majority of the students and offer them a framework to design for assembly meaning. Nevertheless, the results also suggest that we may not impose students to use them but to let them consider themselves if the tools have value for them or the process.

5 *Conclusion*

This paper discusses a case study in which students were offered a methodology and tools to design for meaning in assembly. The methodology and the tools were applied on existing products and after analysis of the assembly process. A project based learning setting in cooperation with a company provided the context needed to learn how to apply the framework and the tools. The different stages of the project (i.e., individual stages of analyzing the existing product and assembly process, and generating ideas to improve the intuitiveness of the assembly process) in combination with a final group stage shows to be very valuable. The individual stages forced the students to come up with own results in order to enter the final stage in which they formed teams. This final stage was important to let the students learn from one another and to decide which solution was best for the product without trying to push their own ideas. The results and feedback of the company also illustrated that the solutions found by the teams were interesting and mostly feasible. The students also considered different solution spaces (e.g., components and subassemblies, tools, jigs and fixtures, the environment and the process itself) to find the most appropriate solution. From the survey with the students we can conclude that the framework and a majority of the tools helped many students during their project but that for some students following a method and using tools feels restrictive and limiting creativity. The case study offered insights that are useful to fine-tune the methodology and the tools but also for implementing it in a PBL setting. The added value of offering students a framework and tools to design for meaning in assembly and to implement this in a PBL course where they have access to the company, the operators for analysis, the products and prototyping facilities was also illustrated.

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