LEARNING ACTIVITIES TO DESIGN A PARAMETRIC SOLUTIONS SPACE FOR PRODUCTS IN INDUSTRY 4.0

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ABSTRACT

The fourth industrial revolution, Industry 4.0, presents challenges for industrial design engineers. The European Union report on Industry 4.0 highlights trends shaping industrial design in this era (i.e. new technologies, different user expectations, advancements in industry). Among the new technologies, parametric design stands out as a powerful tool for creating complex, customised structures using computational algorithms. Therefore, parametric design might be considered essential domain-specific knowledge for future industrial design engineers within Industry 4.0. This domain-specific knowledge of parametric design involves shaping a solution space (i.e. potential products) through procedural thinking (mind-set shift). Inputs, outputs, and workflows need to be considered and are illustrated in the paper with an example. This enables the creation of unique or small series of products tailored to the specific needs of stakeholders. These products can then be efficiently produced using digital manufacturing techniques. However, current engineering and design education often lacks the necessary teaching and learning activities to prepare students for parametric design and procedural thinking. This paper reports on the implementation of educational paradigms for a course on parametric design with the Grasshopper plugin for Rhinoceros. The course (3rd year Bachelor at Ghent University) introduces students to the principles and applications of parametric design (solution space), as well as to foster their creativity, procedural thinking, and problem-solving skills as industrial design engineers. In this paper we will elaborate on the course structure, illustrate the procedural thinking outcomes and discuss the lessons learned and the implications for future courses and research on parametric design education.

Keywords: Parametric design, Grasshopper, procedural thinking, learning activities, Industry 4.0

1 INTRODUCTION

The emergence of the fourth industrial revolution, Industry 4.0, significantly influenced industrial design engineering education. Motyl et al. [1] stress the need for broader engineering skills and domain-specific knowledge related to this. This knowledge should expand beyond merely smart machines as industry 4.0 will also encompass breakthroughs in both physical and digital realms [2]. Consequently, it is proposed to rethink industrial design engineering education to prioritise problem-solving and innovation [3]. Considering this research, it is evident that Industry 4.0 affects industrial design engineering education. Educators should cultivate digital competencies and design relevant learning environments to meet the demands of these new technologies. The question remains: What should these learning environments entail?

1.1 Parametric design as cross-roads within industry 4.0 trends

A European Union report on learning environments (in general) and foreseen goals for industry 4.0 poses a partial answer as they identified some trends related to industry 4.0. Below, these trends are further explained and specified for the field of industrial design engineering.

A first trend includes **new technologies**, which are stated to be inherently intertwined with both physical and digital innovations are often referred to as 'phygital' [4]. Among these, parametric design stands out as a powerful tool for creating customised structures using computational algorithms. Visual programming in parametric design software enables designers to freely engage with geometry and create personalised solutions.

Secondly**, industry advancements** encompass the adoption of novel technologies within manufacturing [4]. Notably, Dauter [5] posits that Industry 4.0 enables intricate, and innovative designs using advanced software tools and simulations. This necessitates new training programs and educational curricula to prepare industrial design engineering graduates for these evolving demands [6], [7]. This paradigm shift is also evident in the context of the course and the case we discuss in this paper. The students learn how to align the personalised design of a product to the manufacturing, considering the possibilities of digital fabrication techniques and the outputs and inputs needed.

Thirdly, the consideration of **different user requirements** emerges as a pivotal trend. These user requirements encapsulate the needs and expectations of end-users for a product or system, constituting a fundamental influence on the design process [4]. Song and colleagues [8] posit that Industry 4.0 has impacted consumer behaviour, including a growing preference for personalised products. Loy and Novak [3] further underscore that Industry 4.0 facilitates a transition from conventional mass production to bespoke mass customisation. Consequently, this paradigm shift affords shorter product life cycles. Anticipating the trajectory of future user expectations, characterised by a desire for heightened product diversity and personalised experiences, underscores the imperative for agile innovation in product development [4]. The Parametric Concept Canvas (PCC) [9] was used by the students during the project-based part of the course to define which type of personalisation was useful and possible within an Industry 4.0 production system. This PCC lets designers reflect on the value of personalisation and this from different perspectives. However, it also triggers the designer to reflect on how this personalisation can be realised (breakdown between standard parts, interfaces and personalised parts) but also digital production techniques that can be used to realise the personalised elements. As such, it is a suitable tool for our students during the course's project part.

Industry 4.0 clearly offers many opportunities to be able to manufacture small series of products or unique personalised products that have real added value over their mass-produced counterparts. However, it is imperative to recognise that designers occupy a pivotal position in this landscape. Their role extends beyond mere aesthetics, they are tasked with shaping solution spaces that facilitate the creation of bespoke solutions. Computational, parametric flows play a vital role in achieving this in an efficient manner, using the data input to create an output which matches the demands and wishes of the user, and which can be produced in an Industry 4.0 context.

1.2 The need for a change in parametric design education

Computer aided design courses in engineering & design curricula mainly focus on correctly producing 3D geometry for manufacturing purposes. Parametric design is often limited to creating variations of a base geometry in which geometric relationships are more rigidly defined and constrained allowing less variability. In a customisation context the physical manifestation of the geometry is not predefined. The curriculum (i.e., Bachelor of Science (BSc) program in Industrial Design Engineering Technology) lacked a specific methodology/approach and learning activities to rephrase aspects such as functionality and manufacturing in an algorithm. Students are to master the algorithmic way of thinking, which consists of breaking down the worldly processes into representations, simplifying the representations to just their structure, and further simplifying that structure to focus solely on its computable aspects as described [10]. We came across many resources focusing on architecture and furniture design, yet we envision many applications in the domain of product design beyond aesthetic customisation or topological optimisation.

Moreover, learning activities in which parametric design facilitates the designer to really become a meta-designer are important, especially when we consider the added value of personalised products. This was also stated by De Mul [11], "the designer (...) should become a meta-designer who designs a multidimensional design space that provides a user-friendly interface, enabling the user to become a co-designer, even when this user has no designer experience (...). The task of the meta-designer is to create a pathway through design space, to combine design bricks into a meaningful design." Parametric design facilitating the designers to become meta-designers was also addressed in this course.

2 COURSE SET-UP (METHOD)

The course (9 credits, 210 h of study time) was planned in the first semester of the third year from the Bachelor of Science (BSc) program in Industrial Design Engineering Technology of Ghent University (26 students submitted a final report and participated to the examination). The data was collected in 2023.

The students received 12 weeks of theory, complemented with a project in which they designed a personalised product and developed a computational workflow. In this project, the students themselves experienced how they could implement the theory (i.e., on digital fabrication techniques, robotics, personalisation of products, industry 4.0, algorithmic design, etc.) in their specific project (i.e. Project-based-learning, PBL). The lecturer's role was to facilitate this by coaching the students, which is typical for PBL projects [12], [13]. Within the project, students had to design a solution space (not 1 product) that allows to efficiently design and produce a customised product considering a particular stakeholder. This entails students to make a mindset shift towards the design and manufacturing of an instance of a product within the solution space. They must consider the interactions with the algorithm, the inputs, the outputs, the constraints, etc. They had to consider the whole process and identify the added value of this customised product in comparison to mass-produced products. The students used visual programming in Rhino Grasshopper, incorporating user input (choices of functionality, aesthetics, but also anthropometric data) into the design, considering the manufacturability of the personalised product. Below the structure of the course is discussed based on Biggs [14] constructive alignment framework. Biggs' framework consists of three interrelated pillars focusing on learning goals, teaching and learning activities, and assessment means.

2.1 Learning goals

The first learning goal of this course is to teach students how to **efficiently and effectively design solution spaces rather than individual designs with a prototypal physical manifestation**. In such a parametric solution space valuable instances of the product can be created based on an algorithm and different types of input. This demands a mindset shift, because the designer needs to consider a solution space with appropriate restrictions (controlling the algorithm) but not the final product (evolving towards meta-design). The design of solution spaces is linked to the shift towards Industry 4.0 where production systems can efficiently manufacture small series and unique products in interaction with the stakeholder. In doing so, they should be able to abstract functionality into a working algorithm that ultimately generates a producible output. As a second goal, we therefore want to teach students how to **use advanced digital production techniques and materials to strategically and efficiently produce personalised products**.

2.2 Teaching and learning activities

To support this mindset shift, the students were introduced to the Parametric Concept Canvas [9]. By using this canvas, the students are guided to consider different aspects such as functionality, aesthetics, or ergonomics. These can be personalised and linked to the architecture of the product and the manufacturability. Using the canvas should facilitate the development of personalised solutions that have real value.

To support the second learning goal the students received theory courses linked to digital manufacturing, data-driven design, parametric design, visual programming, personalised design and manufacturing. Additionally, there were training exercises exemplifying how visual programming in Grasshopper can be used to develop a flow. This flow uses data as an input to change the parametric model and to develop unique instances within the solution space. However, this solution space was also constrained to ensure the functionality and manufacturability. They had to link their designs to real production facilities, materials and costs. Students build on a 2nd bachelor course on industrial manufacturing methods. In addition, they got more in-depth courses on industrial robot applications and CNC controlled machines. As support for the PBL part of the course, the students are given a list of plugins for Rhino - Grasshopper (e.g. plugins that facilitate building an interface for users to interact with the grasshopper script themselves, or plugin's that can link Arduino output directly into the script). They researched the functionality of these plugins and choose one as starting point for their ideation process. Lastly, during class lectures, students learned to understand the industrial revolution towards industry 4.0 and even 5.0.

2.3 Assessment

Evaluation in this course was done in different ways (see table 1). There was a permanent evaluation based on the project. Additionally, there was an exam and a skills test that assessed visual programming skills. Table 1 shows an overview of these assessments, what was assessed, and how this was carried out.

Table 1. Assessment, what and how it was assessed

	What?	How?
Permanent Evaluation (Project)	Opportunity identification for personalisation	Use of the Parametric Concept Canvas [9] (level of completeness and correctness)
	Ability to link geometry to architecture, functionality and personalisation options of the concept.	Report, CAD – models (Rationale to construct the model and how it was executed)
	Ability to link the output to possibilities in production, connecting production, to shape, material and cost.	Report & Physical Prototype (Selection of production techniques based on presented rationale)
Exam and skill test (formal knowledge)	CAD – model, structure of the script, interaction	Visual Programming Skill Test
	Formal knowledge G – code, Robotics, Industry 4.0	Written examination
	Feasibility and commercial value of the concept.	Project presentation

3 RESULTS (CASE STUDY)

In the project-based learning part of the course, each student developed their own case using a variety of plugins in Grasshopper in which different ways of product personalisation were realised. Plugins were selected by the lecturers (a list was created) based on availability and potential to facilitate processes. The students could select from these plugins based on their needs and the added value for their concept. For example, products were developed using anthropometric data of a user to design a customised product. Typical examples are medical devices such as braces but also customised gloves for target groups that must combine wearing gloves with fine motor activities (the case below). Other projects combine functional personalisation with aesthetic personalisation. The system level (e.g. how data can be collected and used) and then how it can ultimately be produced was considered in all cases. The selection of what to personalise for a certain product category was done by means of the PCC.

The case study presented below entails the design of personalised gloves. The user positions the hand on a measuring device and slides the contact point to the fingertips and edges of the hand. The location of the potentiometer is read by an Arduino development board and communicated to the Grasshopper script (the plugin Firefly was used for this). The 3D representation of the glove immediately adapts to the user input. When completed the 3D model is converted to a 2D pattern which can be laser cut and stitched into a glove. Figures 1 to 4 give an overview of this process in which user requirements are used in the grasshopper script and generate an output which can be used to produce the product. In this case study, a physical interface was built to capture the ergonomic parameters in real time. In other case studies, digital interfaces (i.e., a visualisation grouping the relevant input parameters for the user) were built to interact with the user.

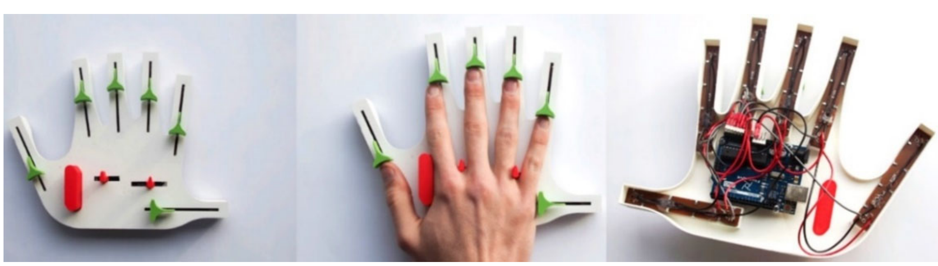

Figure 1. Prototype of the interface developed to measure the hand and to control the script in real time using Arduino

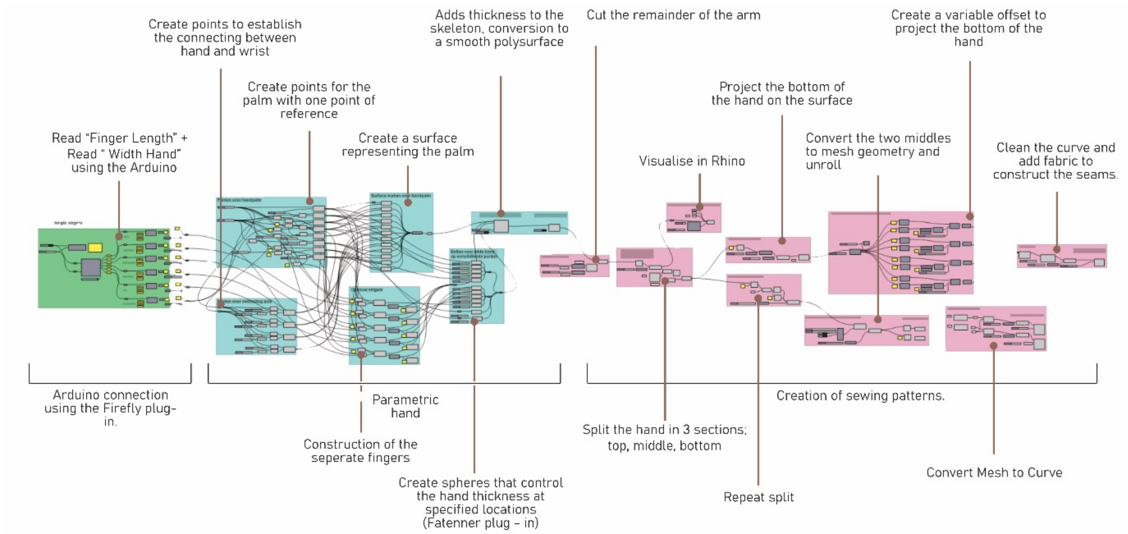

Figure 2. The visual programming script developed in the example case study

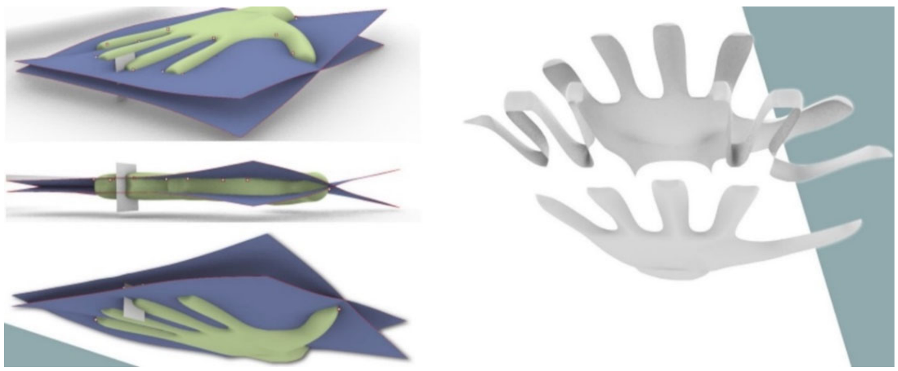

Figure 3. The creation of the sewing patterns out of the 3D model of the hand

Figure 4. The prototype which was developed based on the script

4 DISCUSSION AND CONCLUSION

Although we could only show one student case in this paper, the overall course results indicate that after 12 weeks of courses, most students can make a mindset shift to designing a solution space instead of a product. They manage to develop an algorithm that can generate the necessary outputs (i.e. based on different types of input) to start manufacturing a custom product. Consequently, many students succeed in developing a computational workflow using visual programming, with or without the help of plug-ins. The added value of personalisation was not always clear for every product despite the use of the PCC. This tool proved helpful but couldn't prevent some students from designing some products with limited added value in relation to their mass-produced counterparts. Therefore, the results illustrate that the need for customisability of products is not self-evident. Nevertheless, the results also provided an insight into the abstract thinking capabilities of students. While the majority were able to make a shift from reproducing an idea in CAD to scripting an open-ended algorithm, there were differences in the level of abstraction, complexity of the scripting and functionality of the result. The results also indicated that it was feasible for the students to engage with visual scripting to design parametric flows and geometry which facilitated stakeholder interactions to design a personalised product and for them to become a meta-designer. When considering personalised products, there must be a strong link between design and production. Based on inputs, it should be possible to quickly generate a customised design that can also be produced in an efficient manner. With industry 4.0 in mind, such exercises are crucial to make our designers of tomorrow (i.e. our students) ready for the future. We hope this paper can engage other industrial design engineering curricula to research and develop such parametric flows (from stakeholder to production) within a PBL design context and to integrate similar workflows in courses in their curricula.

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