From Smart Textile to On Demand, Locally Fabricated Design

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In the last ten years, the mass production of goods has been recognized as being highly responsible of having critical impact on the planet. While institutions and policy makers are pushing companies to embrace circular economy, nevertheless new studies are showing that recycling is not enough, if production does not decrease. In this context, the driving force of digital fabrication research is developing an ability to manufacture multiples of one without loss of complexity. This emerging approach is demonstrating that sustainable, high quality, long lasting and affordable products can be implemented through the set up of new business models based on locally manufactured, hi-tech, on-demand products. This paper highlights a preliminary set of implications of the assumed shift from centralized mass production to a distributed micro-factory model through the presentation of the results of a transnational, EU-funded collaboration funded on design-driven services. The workflow that was implemented during the project focused on digitally fabricated items personalized through a fabrication system based on a hand-woven textile sensor matrix that was able to capture unique data from the body. Moreover, the paper describes the key role of makerspaces for enabling an interdisciplinary work environment and creating bridges between textile craft traditions and digital fabrication processes, in order to lower the barriers for design and fashion enterprises to benefit from technological textile innovation in a sustainable manufacturing environment.

Additional Key Words and Phrases: smart textile, microfactory, digital fabrication

1 INTRODUCTION

The delocalization and de-industrialization processes taking place in Italy [1] since the 80s caused a significant dispersion not only of economic and cultural capital, but also of individual and collective skills [2]. This process has dissolved many local relationships between artisans and companies, inventors and industrial districts, with the consequence of limiting the range of produced goods and their evolution.

In Europe, SMEs are the backbone of the economy, providing 85% of all new jobs. In Italy, they represent 78.5% of the "non-financial business economy" employment, against the EU average of 66.4% [3]. Understanding how to make small and medium enterprises more competitive is therefore at the center of many researches, especially when we become aware that a "critical distinction is not between large and small firms but between large and district firms on the one hand and isolated small firms on the other" [4]. For this reason, the EU Commission implemented COSME, an EU programme for the Competitiveness of Enterprises and Small and Medium-sized Enterprises, to encourage them to adopt new business models and innovative practices. The 9-months collaboration, which is the focus of this paper, benefited from an initiative of the programme as it received support to create a unique transnational partnership with the aim to innovate, disrupt and prototype high value ideas. The main objective of our work has been to explore the change in the relationship between design and production - in terms of business models, people, places and technologies - because this has become a central theme in the debate on the 'future of manufacturing'. Additionally, we also wanted to explore the uncharted territories of bespoke furniture since, as Deborah Schneiderman noted,

> it is not unusual for furniture to be designed and built to fit to an interior space, but there is no significant history of commercially available furniture that is made to fit the individual [...] Digital

DOI: https://doi.org/ 10.17028/rd.lboro.9724679

> fabrication technologies introduce a real ability to readily fabricate and make widely available bespoke furniture that is made-to-measure to a space and an individual. [5]

A growing number of labs, such as FabLabs, Makerspaces and Hackerspaces, are becoming places that offer new production facilities, providing infrastructure for experimentation and prototyping that support new forms of local production. These are structures in which an open access to technology and the potential collaboration between participants can lower the barriers to access, especially in design and production processes. Emerging production routines, such as the digital fabrication that is at the center of our experimentation, allowed us to highlight both the critical aspects and the potential for developing these technologies in the small scale manufacturing field.

The production systems that are emerging are in fact based on the combination of on-demand and on-site production, characterized by an innovative interaction between designers working on digital platforms, services and products provided by multinational industries, small businesses and artisans, service aggregators, and local communities. The starting point of our project, called Paramatrix, aimed at developing a pressure sensor matrix made of woven textile to be connected to a parametric design interface able to receive the input from the pressure sensors and use the customers' input data to personalise a parametric object on a digital interface. We wanted to mix the crafting skills of a professional weaver with the possibilities of open hardware and software, to develop diverse bespoke interactive fabrication systems able to meet the creative needs of design and fashion companies and their niches. The objective of the project was to prototype a service which could be purchased by companies wanting to setup a microfactory directly in their retail stores. The service could be tailored to companies' specifications in terms of model and brand details for the final output and allow their customers to experience the interaction with a digital interface and a production unit able to manufacture the item right away. Main feature of the microfactory is to be able to focus on on-demand production in the retail store lowering transport costs and emissions, in order to create more local jobs and supply chain, while avoiding leftovers and storage.

2 OVERALL APPROACH: THE MICROFACTORY

As Neil Gershenfeld explained [6], making technologies more accessible to citizens shows how the goal of personal fabrication is not to make what people can buy in stores, but to make what people cannot buy. Also, the discourse around digital fabrication should not be limited to 3d printing, because it involves many more machines which multiply the capabilities to turn data into things and things into data. In the field of microproduction, a new ecosystem of enterprises is supporting this type of manufacturing, mostly based on open source models and small quantities. We refer especially to four different categories: **producers of technologies** and kits, such as 3d printers, cnc mills, or knitting machines; **manufacturers of materials,** selling with low minimum batch, like conductive yarn, electronic components, or working tools; **service providers** for digital fabrication with no or very low minimum batch, like direct-to-textile printing, metal 3d printing, custom printed circuit board manufacturer; **product designers** with entrepreneurial skills, experimenting new types of consumer products with business models based on on-demand production, like customised glasses, jewelry, accessories and knitwear.

Thanks to these possibilities of experimentation, the activation of new productive subjects and the phenomenon of makerspaces and fablabs [7], we are witnessing a shift in the conception of traditional production places and we start seeing shops, workshops, laboratories and galleries as possible contexts where integrated production modes can be taking place. One of the drives of this transition is the vision expressed by the motto "design global, manufacture local" [8], shared by many makers and designers, so that our society, for many items, could be moving from mass production to on-demand local production, limiting its environmental impact because it would limit waste production, unsold items, transportation and storage space.

Despite all of these opportunities of using digital tools to create new types of digital/physical objects, we have not seen a consistent growth of new businesses. On one hand, some researchers believe that there is still a "considerable divide between the *designer* and the *constructor* of artifacts" [9]. Others also believe that building different type of interfaces, which support embodied real-time interaction and fabrication, enables the proximity of physical input and output, fostering a rapid-prototyping creative process that is more similar to less automated ways of making. On the other hand, "despite the growing number of new tools and technologies, most of them are under-exploited, if not ignored by SMEs [...] the least expensive and least revolutionary technologies (simulation, cloud computing) are the most exploited in SMEs whereas those allowing profound business transformations (CPS, Machine-To-Machine, big data, collaborative robot) are still neglected by SMEs” [10].

With the Microfactory-As-A-Service approach [11], we want to enable interior design brands to setup on-demand manufacturing units in their stores, providing them an optimized workflow to transform real-time sensor input to directly affect fabricated output. Increasing, the ability to adapt production on a moment-by-moment basis would allow low-tech company to fulfill the requests of those ‘markets of one’ and embrace the shift to dynamic mass customization and compete without the need of a big capital investment for machines and skills.

In Figure 1 below, we illustrated the optimised hardware/software workflow we implemented during the research project. It shows a demand-led and not production-led model, to be offered to companies to be setup in their stores or urban facilities, to produce a range of parametric goods according to their brand needs. To build the prototype, we focused the research on an input and an output unit shaped as a chair, but the team is available to develop the workflow on completely different furnishing accessories involving various fabrication technologies like cnc, knitting machines, 3d printers and more.

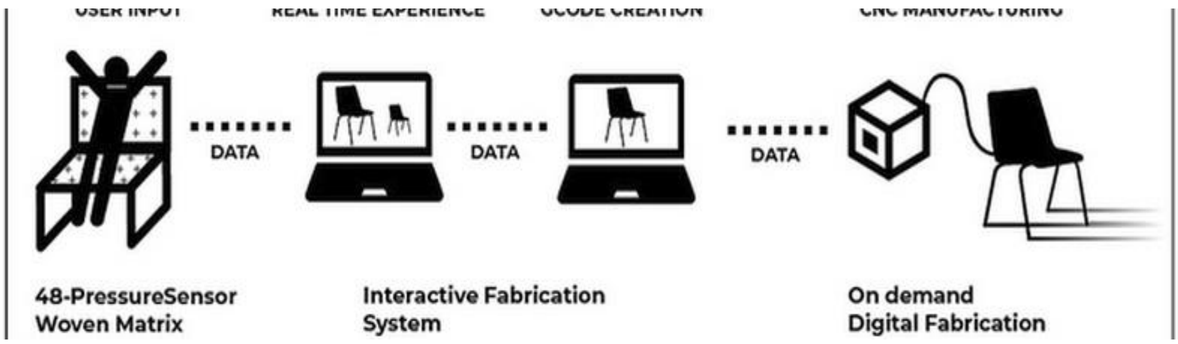


Fig. 1

3 PHASE 1 - SMARTLY WOVEN

The first phase of the project was used to design and produce the 48-sensor textile matrix, in order to meet two objectives: 1) reach a good variation of resistance when sensors are pressed and a quick return to initial value when sensors are released; 2) provide an esthetic quality to the woven piece, exploring different ways to insert conductive yarn in the weaving process. Before starting with the weaving process though, we had to involve a twisting company to produce our own multiple-ply yarn, mixing cotton and conductive thread, because there is no availability on the market of different materials or colors. The direct involvement of the professional weaver allowed the team to benefit from the informal network of relations with companies which could support us and meet our needs in identifying and delivering a custom yarn.

We decided to focus only on one conductive thread which could be purchased in small batches from an online store. The yarn is composed by 20% stainless steel and 80% polyester (2/50 Nm) and is characterised by a high resistance that works well for stretch and pressure . The yarn shows a high resistance while the conductive fibres are close to each other, but as the fibres are pulled apart, the resistance decreases therefore increasing the flow of electric current.

One of the first prototypes which allowed us to test different weaving patterns (Figure 2) had warp of 100 % cotton and reduction warp of 12 threads / 1cm, with different color surfaces reflecting different way to organize the warp on the left and right side.

At the beginning we replicated Hand Woven Waffle Fabric Sensor, the honeycomb structure sample created by Kobakant [12] in order to:

- Test the performance of the custom yarn in comparison to previous experiments
- Activate the interdisciplinary conversation among the professional weaver, the designer and the interaction developer, in order to improve the performance of the matrix.

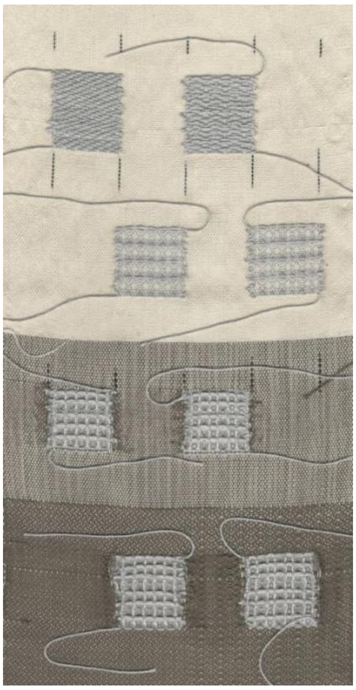


Fig. 2

The yarn performed well enough (Figure 3) to proceed with the following phases, namely to improve the esthetic result and increase the number of sensors to make them act as a matrix.

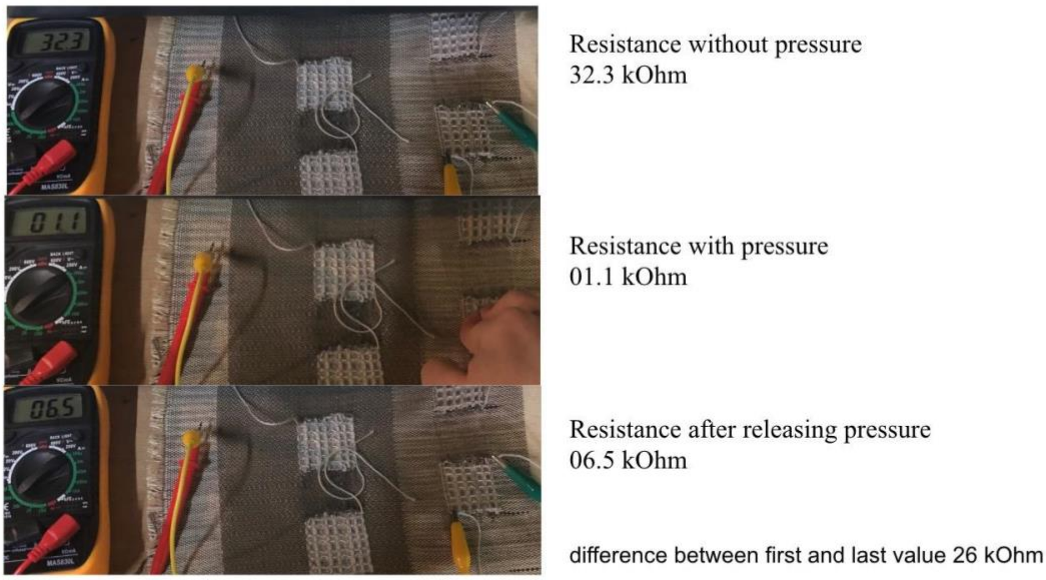


Fig. 3

The conversation among the involved practitioners[1] proceeded slower than expected, because we realised we encountered many misunderstandings on the specific words we were using in our practice and needed to develop a shared vocabulary to communicate properly and move beyond standard routines. As the conductive property of the textile could be improved by the 3d structure of the sensor, it was necessary to translate a very technical language between the two disciplines of weaving and physical computing. In order to overcome the complexity of the glossary and create conceptual bridges in a short amount of time, we organised two sessions of 3-day residencies at the makerspace so that we could abilitate the transferring of the tacit knowledges [13] difficult to articulate other than through intense interaction and shared experience of team members.

On the one hand, the professional weaver could directly experience how the woven pressure sensors were connected to an electric circuit and the reason why some sensors performed better than others. Once the feedback was seen in real time, she could provide alternative proposal to overcome most of the issues the team was facing. On the other, the interactive developer could directly experience the relation between warp and weft in defining 3d structure and tension of the sensor and relate it to its electric performance. The team could perform problem solving strategies on technical tasks because interactions between the practitioners could increase in quantity and quality, and physical proximity combined with mutual interest contributed to the development of shared vision and objectives.

The second series of prototypes allowed us to study different receipts for the weft to increase elasticity with warp's density (Figure 4).

Fig. 4

It was designed according to the feedback and performance of the first series and with the aim of moving beyond the Waffle Weave approach. The prototype sample features warp 100 % Cotton, Nec. 8/2, dark

1 - The team was composed by a professional weaver - Nicoletta Di Gaetano, two interactive developers - Giorgia Petri and Esteban de la Torre and a creative producer - Zoe Romano.

blue, organic cotton. Reduction warp: 11,5 threads / 1cm and conductive Yarn (80% Polyester & 20% Stainless Steel) .

Out of the six samples, after a session of multimeter testing the team chose one sample (Figure 5) because the pressure sensor performed more elastic behaviour thanks to the high presence of wool both on background pattern and sensitive area, especially because of the “3d button” effect that created good return value.

Fig. 5

We then decided to move forward and proceed weaving with the selected pattern, in order to test the performance with multiple sensors connected to the circuit. Figures 6 and 7 show the work in progress of the weaving process.

Fig. 6 Fig. 7

We built a prototype circuit based on the 15-sensor matrix and connected it to an Arduino (see Phase 4 for details) which could feed the data to a computer in order to process data with different softwares (see Phase 5 for details).

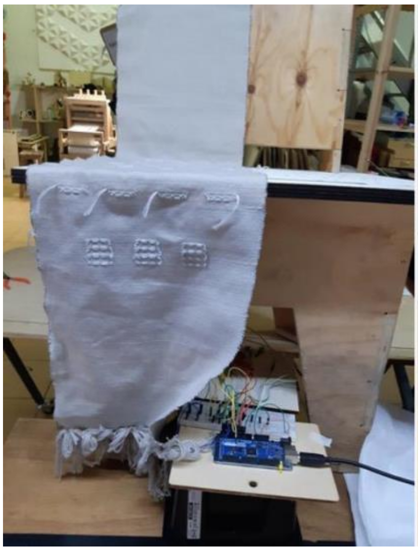


Fig. 8

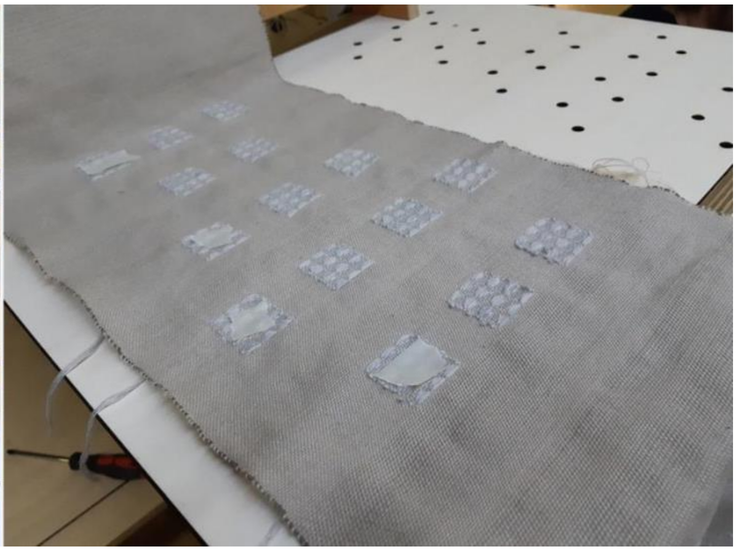


Fig. 9

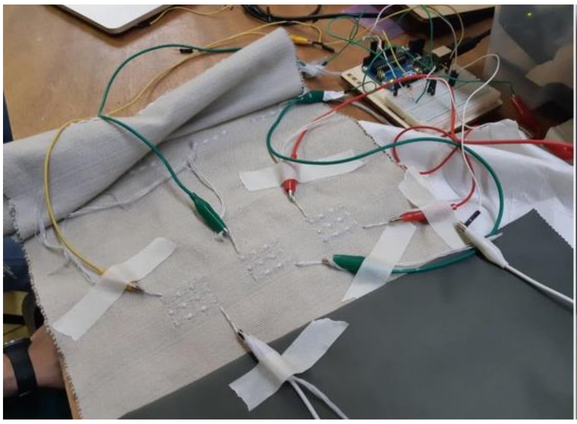


Fig. 10

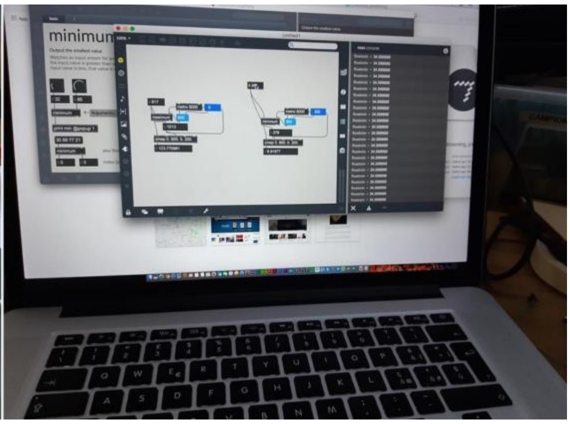


Fig. 11

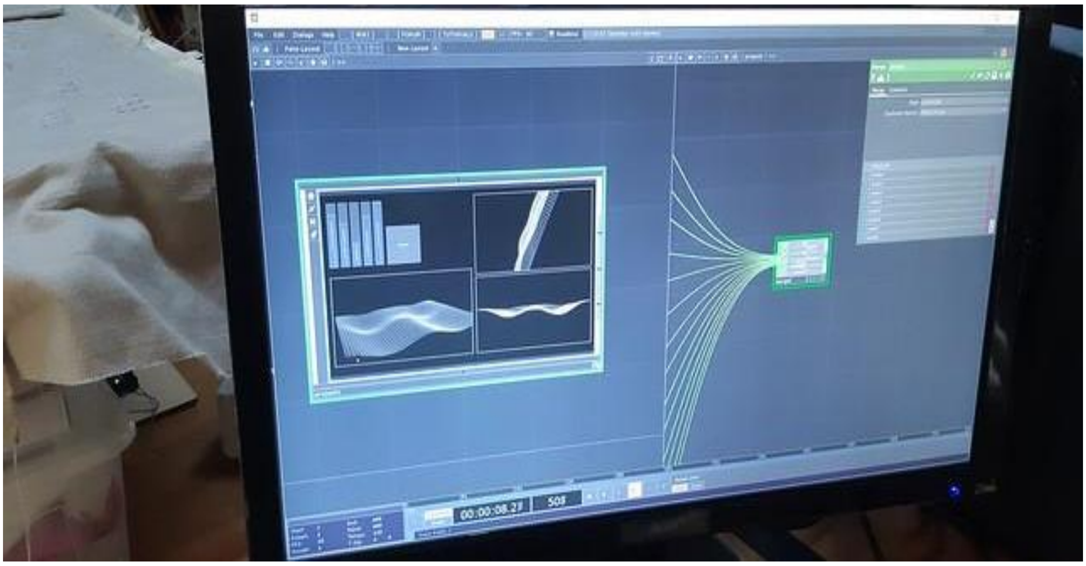


Fig. 12

The data received from the matrix was then used to modify a mesh realtime for the first time in our work. Data were grouped according to the sensor position and equalised to correct the inconsistency of the analog sensors, as most of the sensors' generated data performed differently, especially on the intensity of the pressure and its release value. Each sensor is providing three types of information: regarding being pressed or not pressed (0 or 1), regarding the intensity of the pressure (from 0 to 1023) and the release pressure expressed through measuring variation of resistance. The overall performance was in any case good enough to proceed in increasing the number of sensors using a darker colored cotton from a new manufacturer.

We tested the new non-conductive material (100% cotton) with 1-sensor sample to explore other small variations on the weaving process and then chose the sensor giving best variation and release performance. Figure 13 shows the final sensor choice.

Resistance without pressure

Resistance with pressure

Resistance after release

Fig. 13

Figure 14 shows the work in progress of the weaving of two stripes following the 6x4 matrix measurement and the design of schematic represented in Figure 15. During the project the weaver used an 8-heddle loom for its practical size and portability, and we accomplished the task of having 48 sensors manufacturing two stripes of textile.

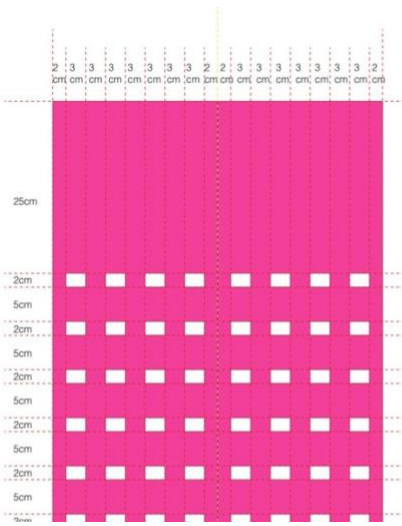


Fig. 14

Fig. 15

The final result of the weaving process (Figure 16) achieved the objectives of aesthetic distinctiveness for the integration of conductive and non-conductive yarn and met the functional aspects required by the circuit (Figure 17).

Key aspects of this phase was the knowledge developed during the residency and involvement of the weaver in previous training sessions on Arduino and the basic rules of electronic circuits and e-textiles, which allowed the team to quickly exchange information and contribute to the overall improvement. The lack of hierarchies at the makerspace provided an unbiased environment, as it was neither an engineering research center, nor a weaving lab, the team could have the freedom to explore different routines in the research process without the pressure of following specific disciplinary habits.

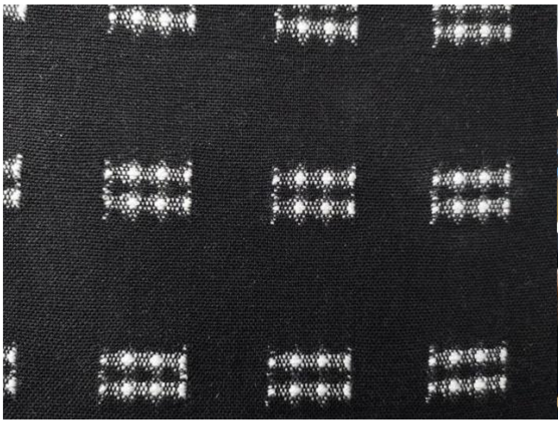


Fig. 16

Fig. 17

4 PHASE 2 - BUILDING THE CIRCUIT

The second phase of the project saw the involvement of the interactive developer[2] and interaction designer[3], which had the task to control a range of buttons (maximum 48) to collect data for customizing the digital mesh in real time. The team tested the following options:

1. Arduino Mega - 12x12 matrix
2. Textile xy matrix with sandwich
3. Shield MUX [14] (multiplexer) - 48 analog/digital input
4. I/O expander PCF8574 o MCP23016/17 - 16 input

After various testing and previous experience, the best solution came to be number 3: the MUX shield with an Arduino Uno. An electronic circuit was implemented to read data from the sensor (Figure 18).

2 - Giorgia Petri
3 - Francesco Perego

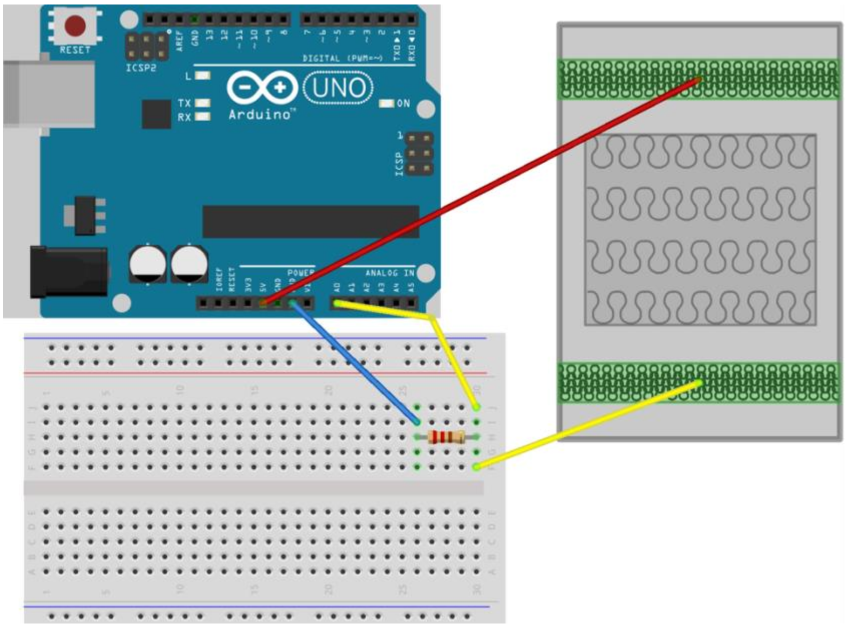


Fig. 18

In order to avoid use of crocodile cables and reach a stable connection, the team had to test different tools and components taken from jewelry craft (metal beads) and music equipment (jack connectors) to create bridges between the softness of the yarn and hardness of Arduino pins without dissipating conductivity features. The team built a jack-connector layer (Figure 19) mirroring, on a wooden board, the textile matrix sensors above and the area below the wooden board could host all the connections (Figure 20), which brought data in the Arduino-compatible MUX Shield. The use of jack connectors, mostly utilized in headphones, facilitated the act of assembling and disassembling the circuit for transport.

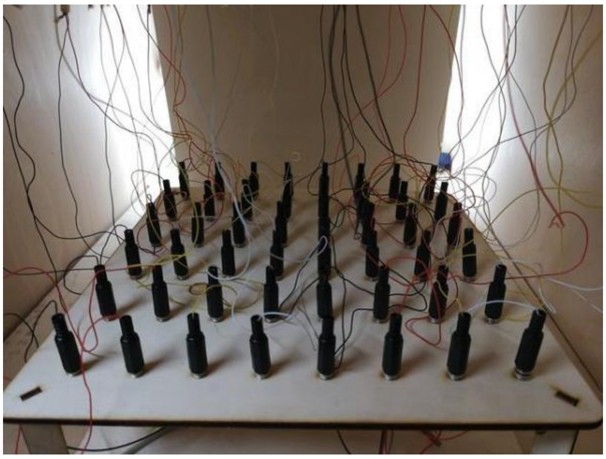


Fig. 19

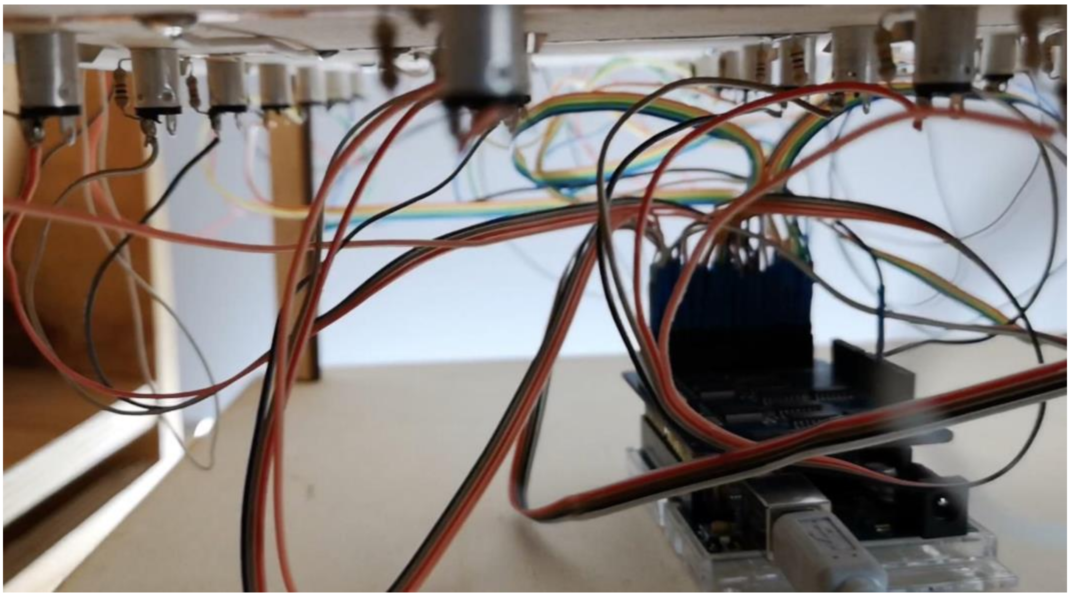


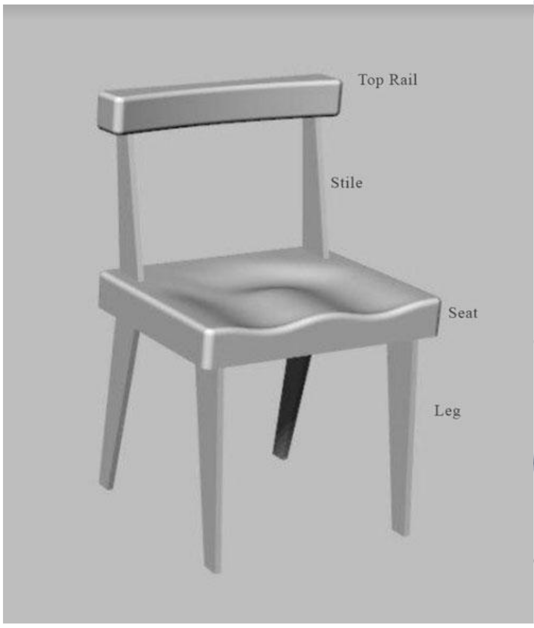
Fig. 20

Despite the increase of the quality and quantity of components available on the market, the team encountered a lack of commercial offering regarding tools, components and materials in the field of e-textiles, even if this research & development area has now been active for several years. The lack of specific tools and suppliers is a barrier to innovation. If we want to foster the integration of textile materials with electronic components it becomes crucial to create new tools because, as Irene Posch and Geraldine Fitzpatrick highlighted, "not only aesthetic decisions influence the next step to be taken, but also electrical aspects not per se visible to the human eye [15]. Also in this case, the fact that the practice-based research was taking place in a makerspace allowed the team to get exposed to different tools and materials specific to diverse practices. This new type of proximity is possible because people with diverse backgrounds, working in makerspaces and fablabs and embracing a maker attitude, are very often merging digital tools with traditional practices.

5 PHASE 3 - PROCESSING DATA FOR CNC PRODUCTION

In the third phase the interactive developer and the computational designer worked together to convert the data coming from the matrix into a variation in the design parameters of the resulting chair.

The computational designer, as an expert of CNC manufacturing, designed a 3d model (Figure 21) of a chair composed by some static parts: legs, stiles and top rail; and a parametric part, the seat, which is the customisable part, digitally and locally manufactured in a short timeframe, using the material selected by the customer. The mesh was designed using the software Rhinoceros and its plugin Grasshopper. The latter is primarily used to build generative algorithms and gives the ability to change the shape of model geometry as soon as the dimensions' value is modified. The surface of the seat is modified by the data coming from the Arduino, and received by the interaction of the customer with the 48-sensor woven matrix (Figure 22).



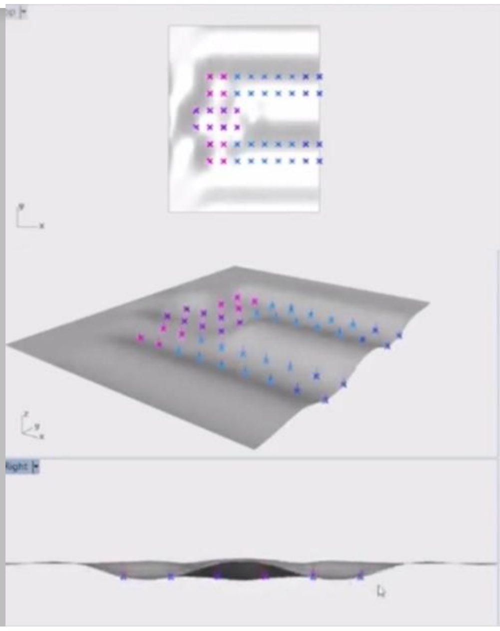


Fig. 21 Fig. 22

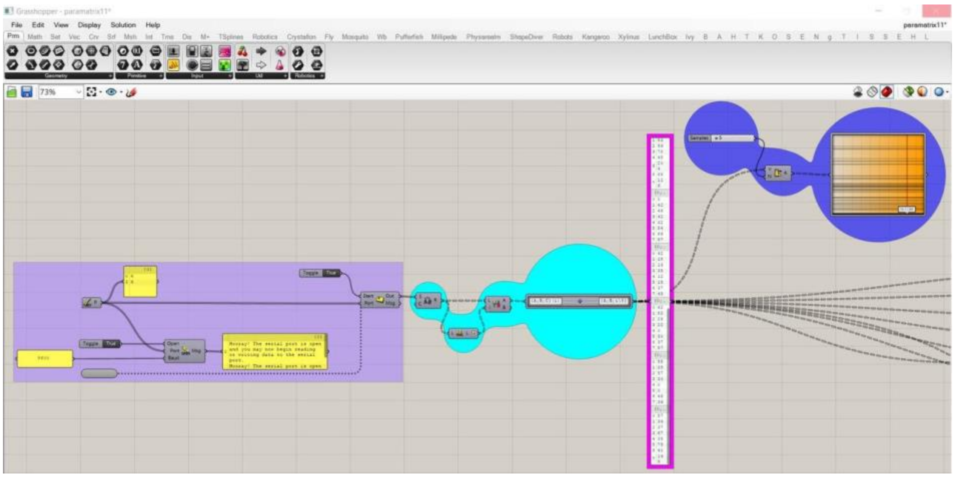


Fig. 23

The algorithm programmed in the software creates the relation between the input data and the output data and allowed us to correct inconsistencies coming from the analogue sensors (Figure 23). For example, we realized that when pushing the textile sensors more than once consequently, it didn't allow the sensor to go back to the zero level. Therefore, we had to spend more time on calibrating the sensors, reprogramming the software, and exploring various use cases with the collaboration of different people testing the matrix.

The algorithm generates two types of mesh variation: the first modifies the shape of the 3D seat according to the weight and position of the person seating and the number of sensors actually pressed, the second uses a multiplier to create a detailed decoration on the surface (Figure 25 and 26) in order to diversify the seat considering that there could not be much difference between the shape and weight of people's bodies. After testing the workflow with the variations of the seat according to the input of different body shapes and weights (Figure 27), we could finally calibrate it to process bodies which had little variation in shape and weight and proceeded to produce a final design chair based on one of the users (Figure 28).

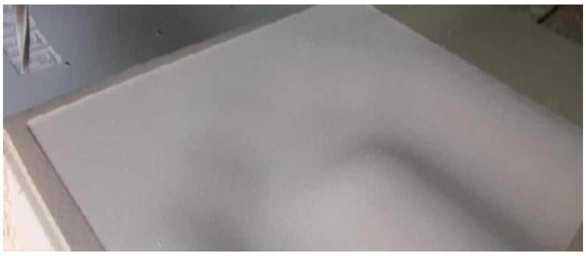


Fig. 24

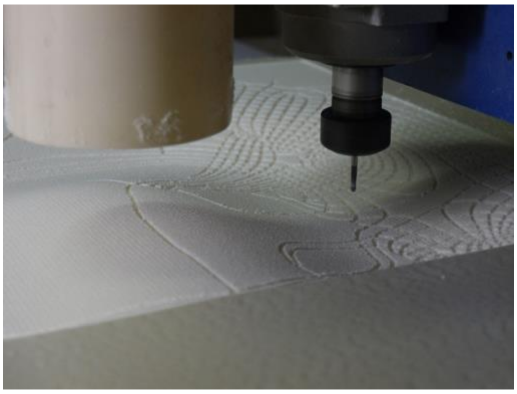


Fig. 25

Fig. 28.

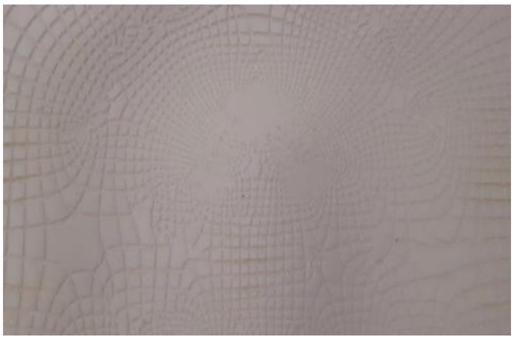


Fig. 26

Fig. 27

The workflow is complete when the software generates the G-code which draws the toolpath of the machine and manufactures the seat using the selected material[4].

CONCLUSIONS

In 2018 McKinsey published a report titled 'Is Apparel Industry Coming Home?' exploring how nearshoring, automation and sustainability are establishing a demand-focused apparel value chain. In those pages, they highlighted very clearly the necessity to induce the apparel industry to change its production models: "Only if companies transform from the historical *supply focus* to a *demand focus* can they stay relevant for consumers and improve top- and bottom-line performance [...] speed and agility are now on the radar for winning apparel players and on-demand replenishment has increasingly become a make-or-break capability" [16]. At the same time, according to a report released in 2012, "a quarter of the

4 - See video https://www.youtube.com/watch?v=5PgJ26ZBEKg and more pictures https://www.flickr.com/photos/wemake_cc/albums/72157672360402037

world's furniture is produced in the EU.20 [and] the role of Germany, Italy, Poland and France (which rank among the Top 10 furniture manufacturers worldwide) is particularly important as they have a combined share of 13% of world production and almost 60% of total EU production" [17], even though the production has been constantly contracting since the beginning of the '00s.

Many multinational companies, like Amazon, are filing patents [18] to become key players in the transition from the "Produce, Sell, Deliver" to the "Sell, Produce, Deliver" paradigm, which is more likely to meet the demands of a new generation of consumers, piloting on-demand manufacturing solutions in various industries. They invest consistent R&D resources to move towards total automation options and acquisition of proprietary fabrication systems in many areas of design, like fashion and interior design. And what about SMEs?

Medium and large size firms are making important investments to optimise production and achieve scale economies with Computer Assisted Manufacturing (CAM) solutions and Computerised Numerical Control (CNC) machines [19], but only for traditional manufacturing, without exploring possible solutions and areas of development related to the latest trends:

> as consumer demands shift toward personalization, customization, and creation, we will see an increasing proliferation of niche markets where, rather than "settling" for mass-market products, consumers will be able to find or even create products suited to their individual needs. In this environment, manufacturers fully leveraged to produce large volumes of limited numbers of products will likely be at a disadvantage, forcing them to rethink their place in the manufacturing landscape and the value they bring the consumer. [20]

The research in Paramatrix project allowed us to explore the concept of Microfactory-As-A-Service, in order to boost more sustainable approaches of demand-focused furniture using smart textiles and a CNC machine. The objective was to provide a more accessible way to small-medium enterprises to enter this new type of marketplace without investing large investments in R&D. All the phases of the project encountered specific issues that were solved and explained in the previous chapters. In more general terms, we were able to accomplish our main task - to create an optimized workflow - because, on the input side, we could use accessible materials and an open standard (Arduino) to read the sensors and transfer the data to a custom software generating the instructions for a cnc machine or a six-axes robot. Both machines can be, in fact, controlled through the G-code, a standard code containing all the instructions telling the motors where to move, how fast, and what path to follow. Paramatrix represents a proof of concept, showing how the interdisciplinary skills available in a makerspace and the rapid-prototyping approach of the team provided an ideal environment to put together the building blocks of an alternative workflow able to fill the gap of the new customers' demand. We used specific technologies which were available in our fablab and were open enough to be used in ways not expected by the producers. In theory, we could potentially have used other machines to create an output interpreting the data, like a computerised knitting machine, a computerised loom or and embroidery machine. This is the opposite of those professional machines that are not working through a shared language, a standard to allow a third party to operate the machines with a different software, other than their own proprietary software which does not provide the sufficient openness for these kinds of experimentation, like some already existing DIY machines[5]. The main difficulties we encountered emerged in particular when all involved professionals needed to understand each other and collaborate and also in the way we were prevented to access specific machines to test innovative paths, consequently limiting the chance to create alternative solutions in the emergent textile sector. This is not a matter of open sourcing proprietary software, but rather of opening doors to allow direct communication with machines and multiply their possible uses to bring the industry to a new, more sustainable ecosystem of innovative creations, fostered by the tinkering skills of makerspaces and fablabs in collaboration with the creative potential of small and medium enterprises.

5 - Ayab project is a maker-friendly approach to vintage knitting home-machines https://ayab-knitting.com/

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