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To cite this article: Jose Antonio González Ruiz, Norbert Blanco & Marc Gascons | (2022) Enhancing process performance for composite padel racket manufacture using Six Sigma-DMAIC and VSM synergetic support, Cogent Engineering, 9:1, 2084982, DOI: [10.1080/23311916.2022.2084982](https://doi.org/10.1080/23311916.2022.2084982)

To link to this article: <https://doi.org/10.1080/23311916.2022.2084982>



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Published online: 10 Jun 2022.



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Received: 23 August 2021  
Accepted: 28 May 2022

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Reviewing editor:  
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## CIVIL & ENVIRONMENTAL ENGINEERING | RESEARCH ARTICLE

# Enhancing process performance for composite padel racket manufacture using Six Sigma-DMAIC and VSM synergetic support

Jose Antonio González Ruiz<sup>1\*</sup>, Norbert Blanco<sup>1</sup> and Marc Gascons<sup>1</sup>

**Abstract:** In the mass production of composite materials, an unrealistic interpretation of specific parameters such as raw material consumption or cycle time per process may be counterproductive to business performance. This study proposes integrating a lean tool (Value Stream Map) into a DMAIC-based approach to improve process performance in composite padel racket manufacturing. The system presented is particularly useful in mass production as it is a customer-driven approach that aims to reduce waste (both material and time) and variation, thereby enhancing the quality of end-use composite products and their common manufacturing processes (cutting, laminating, and curing). The proposed procedure's effectiveness in improving CoFRP processing within the sporting goods industry is noteworthy as

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### PUBLIC INTEREST STATEMENT

As waste elimination (both material and time) procedures are uncertain in most scenarios, in this work a Value Stream Map (VSM) is introduced into the structured problem-solving procedure Six Sigma to guide waste elimination. The VSM tool is used by a wide range of organisations to represent production flows, identify waste locations in a process and enhance process efficiency, while Six Sigma focuses on improving product quality by decreasing defects (scrap) and process variation. This study implements, for the very first time, the VSM tool within the Six Sigma methodology to define, measure, analyse, improve, and control (DMAIC) the manufacturing process for continuous fibre reinforced plastics padel rackets (CoFRP). As a result, cost savings and process efficiency increased by 18.5% and 15%, respectively, over the entire manufacturing process. The methodology and findings from this study can be generalized and employed in any manufacturing plant using composite materials.

cost savings and process performance have been increased by 18.5% and 15%, respectively, in workstations where advanced composite materials are processed.

**Subjects: Transport & Vehicle Engineering; Clean Tech; Environment & the Developing World**

**Keywords: composite production; VSM; DMAIC; Lean Six Sigma; case study**

## 1. Introduction

The challenge to manufacture large series of composite parts stems from the needs of new markets such as the automotive or sports goods industries, where the knowledge and technologies acquired from aeronautics and aerospace fields can be used to great potential (Barile et al., 2019). Market trends indicate that composite material applications are evolving towards higher numbers in volumes. Thus, a more comprehensive knowledge of the serial production of composite parts is required. For instance, automotive applications require highly automated and robust production technologies, which can be notably expensive in terms of investment. However, production will still be economically feasible as long as material costs are affordable (Henning et al., 2019). Instead, the sports goods industry is focused on semi-automated processes with much more manual labor applied because the production quantities are usually not as high.

The potential for applying structural composites to the sporting goods industry is remarkable (Li & Zhen, 2011; Spencer, 1998; Su, 2014). For instance, in recent years the demand for padel rackets made of composite materials, specifically carbon fibre reinforced polymer (CFRP), has grown significantly thanks to the extremely light, resistant, and fashionable product obtained. Thus, the consumer is willing to pay a higher price for a padel racket made of composite materials if the quality and performance of the product are excellent. Although a padel racket's durability is extensive, nowadays there is a global concern about the low recyclability of the most common combination of fibre and epoxy matrix. The wastage generated when a padel racket is produced, as well as the rejection rate, do not only contribute to environmental degradation, but also have an adverse effect on the product's profit margin. Although still a challenge, research has been and is being conducted to develop effective recycling methods for carbon fibre reinforced composites (Memon et al., 2020). In this specific industry, the problem described is exacerbated by high production costs (material and time consumption), the moderate variability of processes (highly manual process) that often decrease product quality, and generalized industrial secrecy. This adverse combination hinders high-performance composites entering the mass-production market.

Based on relevant literature, many researchers have integrated lean methodologies and Six Sigma (LSS) to face challenges similar to those described above (Hung et al., 2015; Jamil et al., 2020; Nagi & Altarazi, 2017), even in the composite industry (Thomas et al., 2016). Six Sigma entails a project-based approach aimed at improving the process and quality of the product (Schmidt et al., 2018). For process improvement, Six Sigma is carried out using the DMAIC methodology throughout the define, measure, analyse, improve, and control phases (Schmidt et al., 2018; Sin et al., 2015). In recent years, research has been conducted into finding the most adequate systematic approach to eliminating flaws that lead to rework and scrap via a custom integration of systems adapted to the particularities of each industry (Smith, 2003). In this context, and according to the literature, the integrated hybrid model in which the Value Stream Map (VSM) is part of DMAIC, is one of the most effective approaches to reducing defects and drastically decreasing rejection rate, and thus leading to remarkable cost savings (Guo et al., 2019; Syaifoelida et al., 2020). Most publications on VSM and Six Sigma DMAIC address several quality-related issues (Kumar et al., 2006; Rachman & Ratnayake, 2018; Wong et al., 2019) but, for the composite

industry, little research has been found on identifying and evaluating significant factors that cause internal waste within a framework of continuous improvement.

This study aims not only to identify the root cause of the rejection rate, but also to identify, understand, quantify, and minimize waste (both material and time) which will ultimately enhance cost savings, process performance, and customer satisfaction. To achieve this, the VSM tool must be considered in the present approach, given its effectiveness in representing production flows and identifying most types of waste (Dinis-Carvalho et al., 2015). However, as waste elimination procedures are confusing and undisciplined in most scenarios, VSM should be introduced into a robust and structured problem-solving procedure like DMAIC methodology for guiding waste elimination (Parv et al., 2019). Therefore, this study deploys the DMAIC cycle within the composite manufacturing in order to understand, quantify, and reduce the waste previously identified by VSM and other complementary tools highly oriented towards the search for material waste (e.g., materials flow diagrams). Although the proposed approach has been validated in a manufacturing line of composite padel rackets, the present paper aims to establish a well-defined framework based on DMAIC methodology to systematically guide any continuous improvement project within the general composite industry.

This paper is arranged as follows: Section 2 presents a brief review of the literature focusing on the main challenges of composite processing and the underlying philosophies presented by other authors on the integration of VSM into the structure of the Six Sigma-DMAIC framework. Section 3 presents the research methodology entailing the proposed DMAIC-based approach and Section 4 clarifies the steps included in implementing the proposed approach through an industrial application. Section 5 discusses the effectiveness of the proposed framework and finally Section 6 defines the conclusions and implications of the research.

## 2. Literature review

This section presents: (1) a brief review of the literature focusing on the main challenges of composite processing; and (2) the underlying philosophies presented by other authors concerning the integration of VSM into the structure of the Six Sigma-DMAIC framework.

### 2.1. Composite processing overview

The main challenges especially related to mass production manufacturing of continuous fibre reinforced plastics (CoFRP) are threefold. The first is the high cost of the raw materials involved. Hence, these costly materials must be used optimally to minimize material consumption and avoid production waste (Eck et al., 2015). The second challenge for CoFRP manufacturing is processing complex geometries, all the while avoiding manufacturing defects such as gapping, porosity, incomplete filling, or fibre wrinkling.

Furthermore, for reasons of quality and because it is a well-understood process, most parts are conventionally cured in autoclaves. There is a body of in-depth research into the four key issues in autoclave curing process control and optimization, i.e., the effects of heating rate, laminate thickness, bleeder process, and convective heating (Aleksendrić et al., 2016; Nele et al., 2016). Because of these factors, a number of researchers have been working on decreasing the cycle time in the autoclave through thermal inertia analysis and by taking into account the relative geometry of the part-tool assemblies (Li et al., 2018; Telikicherla et al., 1994). However, the time reduction that can be achieved in this way is not enough to be applied in any high-volume manufacturing line.

As for the third challenge, achieving lower processing times, manufacturers for high production markets cure composite materials through conductive thermal curing, especially in hot presses (out-of-autoclave process). Hot presses are very well suited to snap curing thermosets or thermoplastics

owing to a very effective heat transfer. In that way, the compression moulding press can reproduce composite parts in significant volumes, with the accuracy, repeatability and speed required. Thus, thermoforming processes could be used to enable automated manufacturing solutions (Manson, 2004). Although curing using a hot press may seem an appropriate way for high-volume manufacturing of advanced composite parts, as with the second challenge, there are limitations that need to be considered. For instance, when compression is applied over the mould, fibres may move thus compromising strength and aesthetic appeal. Such distortion or fibre waviness could negatively impact the distribution of forces within the part, thus reducing its overall stability which is a critical concern especially for structural parts requiring impact resistance (Kulkarni et al., 2020).

Microwave processing of carbon fibre-reinforced plastics (CFRP) is an alternative to conventional thermal processing techniques thanks to its potential to reduce part processing times and mitigate the bottleneck that often exists in composite component production. This processing technique is promising but has notable limiting factors which have reduced any massive acceptance in the industry. For instance, problems associated to microwave energy distribution, arcing, tool design and part quality and consistency, have led to considerable scepticism about the technology for heating such type of materials (Zhang et al., 2018; Zhou et al., 2019).

## **2.2. Six Sigma-DMAIC and VSM applications**

In mass production, Six Sigma is particularly useful because it is a customer-driven approach that aims to reduce variation, thereby enhancing the quality of a product or process. In recent years, Six Sigma methodology, through the DMAIC approach (Define, Measure, Analyse, Improve, Control), has been demonstrated to be effective in improving manufacturing processes in multiple sectors such as health-care, metallurgy, consumer goods or aerospace, among others (Barbosa et al., 2014; Girmanová et al., 2017; Hill et al., 2018; Kozaczuk & Zalewska, 2016; Kumar et al., 2006; Osore et al., 2020; Rachman & Ratnayake, 2018; Sajjad et al., 2021; Thomas et al., 2016; Wong et al., 2019). Implementing the DMAIC approach of Six Sigma in the composite manufacturing was reported in a recent study (Larsson et al., 2022). The European manufacturer involved aimed to reduce manufacturing-induced visual deviations which led to scrapping cylindrical fibre-reinforced polymer (FRP) bodies. The production scrap rate was substantially improved compared to the historical level (60%) and ultimately reached an acceptable 5%, thus leading to increased quality, competitiveness, and substantial savings.

A key component of Six Sigma is the statistical and graphical analysis which includes tools such as the Value Stream Map (VSM), Pareto charts, histograms, and control charts to obtain an in-depth understanding of the processes and to demonstrate the project's return (Elkin, 2008). One of the most effective tools for exploring waste locations in a process and enhancing process efficiency is the Value Stream Map (Rother & Shook, 1998). That said, an initial activity to reduce waste and improve productivity through VSM is to first analyse Value Adding Activities (Henning & Moeller, 2011; Shou et al., 2020). Some researchers have evidenced that lean improvement based on VSM is outstanding regardless of the field in which it is applied (Abdulmalek & Rajgopal, 2007; Carmignani, 2017; Chang et al., 2020; Gracanin et al., 2014; Gunduz & Naser, 2017; Rajesh et al., 2019; Seth et al., 2017). Chiun-Ming Liu (2012) proposed implementing lean techniques based on VSM to improve the efficiency of the composite-material bonding process, shorten delivery times, and speed up responses to customer demand. By comparing the value stream maps before and after lean techniques such as 5S and Kanban had been implemented, the results suggest that process cycle efficiency increased from 1.99% to 4.97%.

Many other researchers have integrated the Value Stream Map (VSM) tool into DMAIC methodology to enhance productivity (Guo et al., 2019; Hung et al., 2015; Syaifoelida et al., 2020). According to the attributes and applications of VSM and DMAIC, there are essentially two notable integration model types (Salah et al., 2010). The first presents DMAIC as part of VSM that identifies

and locates waste and production problems from current to future VSM. This kind of model is close to the integration proposed by Guo et al. (2019). These authors developed the integration of DMAIC into VSM supported by concurrent Lean-Kaizen and the dynamic updating of production problems to increase profitability. The results from their study show assembly-line performance improved by around 15%, thus being far more profitable and efficient than ever before.

The second model type introduces VSM as part of the DMAIC, which then acts as a tool for supporting the specific DMAIC phase. This kind of integration is often called Lean Six Sigma, and most scholars focus on this type of model. For instance, in another relevant study, Nagi and Altarazi (2017) demonstrate the coherent implementation of several quality tools (fishbone diagram, control chart, Pareto analysis), strategic layout planning and VSM within the DMAIC approach to reduce the occurrence of different types of nonconformities in the carpeting process. As a result, process capability, product quality, customer satisfaction, and the consequential costs of poor quality, were significantly improved because of the number of defects was reduced by (approx.) five times. In any case, and regardless of the integration model, Hann et al. (2007) note that applying quality programs to reduce operational inefficiencies and waste always requires the involvement of top management and a commitment to providing appropriate training and resources.

An extensive study within the composite industry (Thomas et al., 2016) described the application of a strategic Lean Six Sigma framework by integrating VSM into the DMAIC cycle. The researchers were able to achieve greater production efficiency while also ensuring that Critical to Quality (CTQ) issues were eradicated from the production process. The key improvements seen were as follows: 20.5% build-time reduction, 26.5% improved customer-delivery time, 5%, reduced value-added time and 44.5% reduced non-value-added time; all leading to significant financial savings. Another study conducted by the German Aerospace Center (Al-Lami & Hilmer, 2015), which aimed to contribute to a more cost-effective and environmentally-friendly composite production process, also successfully implemented VSM concepts into the DMAIC framework but, in this case, this was aided by several decision support tools such as the Life-Cycle Assessment (LCA) and the Life-Cycle-Cost Analysis (LCCA).

Most publications on Lean Six Sigma (LSS) in composite manufacturing mainly address quality-related and process efficiency issues, as well as recyclability concerns in some cases. However, composite waste is scarcely tackled in the LSS framework. A relevant work (Rybicka et al., 2015) aimed to demonstrate the waste produced from manufacturing processes, and characterise the types of waste at the scrap creation point. Through case studies, they identified three fibre related waste outputs: dry fibres, fibre material sheet off-cuts, and cured composite off-cuts. To do this, the researchers conducted a Material Flow Analysis (MFA) based data-collection workshop with four composite manufacturers. In a similar study, Shuaib et al. (2015) address—with the aid of Sankey diagrams (a visual representation for material resources)—waste volume generated from virgin material in the UK. The objective was the efficient use of manufacturing and end-of-life composite waste. Nevertheless, little evidence has been found on identifying and assessing any significant root causes that cause excessive composite waste during the entire production process.

### 3. Research design

The academic literature indicates that the relationship between lean manufacturing and Six Sigma has been studied mainly in relation to any potential benefits their integration may provide in different contexts. Since both approaches have unique features and benefits, of which only the most effective combinations would be retained, this section aims to address the critical question that arose, “How can the two approaches be effectively combined into one system for in-depth assessment and reduction of both key parameters (waste and scrap), thereby increasing business performance within the composites industry?”. Many researchers have integrated the Value Stream Map tool into DMAIC methodology to enhance business performance (Al-Lami & Hilmer,



2015; Thomas et al., 2016). As shown in the literature review through the relevant study performed by Nagi and Altarazi (2017), Lean Six Sigma methodology (integration model in which VSM is part of DMAIC) is one of the most effective approaches to increasing process efficiency and drastically decreasing rejection rates and, thus, leading to relevant cost savings. In this manner, most publications address a number of quality-related issues, but little evidence has been found on identifying the significant factors that cause internal waste, particularly in the composite industry.

In the current study, the VSM tool is employed to identify waste, reduce process cycle times, and increase process efficiency by decreasing NVA activities. Moreover, VSM involves constant implementation plans for continuous improvement at value-stream level (Jamil et al., 2020). To be more effective, a continuous improvement process where the current-state map is frequently updated should be considered as this is an effective way to show the levels of improvement attained after each new improvement study. In this context, the VSM tool should be introduced into the DMAIC problem-solving model to guide waste elimination (Parv et al., 2019) and enable the deployment of this lean tool in a systematic, repeatable, and continuous cycle of improvement. Therefore, the DMAIC cycle is executed to understand, quantify, and reduce the waste previously identified by VSM and other supporting tools like Material flow analysis (MFA), within a tailored framework for continuous improvement. This will ultimately result in enhanced cost savings, process performance, and customer satisfaction. Likewise, more affordable and sustainable composite products will be manufactured.

This study provides a unique feature of sequencing and linking lean and the Six Sigma tools during the five phases of DMAIC. The proposed integrated framework is presented in Table 1. The tools needed appear in a chronological order of application and the research phases of the methodology are developed below.

### **3.1. Define**

This phase consists of clarifying the project's scope, identifying the problem, and defining the goals. However, the first step towards solving any problem in Six Sigma methodology is by forming a team associated with the process. In this study, the team-build session was conducted through a series of meetings with departmental heads in the organization to help select individuals with the skills, passion, and knowledge of the process needed. Afterwards, an introductory meeting was held with the selected members making up the target group to share ideas and understand the need to establish a learning community within the process cycle. In addition, this group also received external training sessions. The team's objective was to develop common skills for Six Sigma-DMAIC improvement strategies, as well as to harness knowledge and share expertise among the participants. A moderator was appointed based on their knowledge about the wide range of topics that were discussed during the meetings. The members held short follow-up meetings at the beginning of every workday and interacted face-to-face, or via email or Microsoft Teams. The team drew up the project charter which contained all the necessary details of the project such as its background, the reason for selecting the project, the objectives and expected results, the project team/formation, the Voice of Customer within the project, and the length of project. When drawing up this working document, the basic metrics and a data collection method should also begin to be defined.

### **3.2. Measure**

This phase consists of establishing reliable and applicable metrics to help monitor key process characteristics, the scope of the parameters considered and their performance to understand their progress towards the objectives established in the define phase. Once the waste and its corresponding metrics (i.e., internal rejection rate, raw material waste, cycle time or value-added time) were defined and the data was collected to feed these metrics, current material flow diagram and as-is VSM studies were conducted to identify the sources of waste (material and time) and

Table 1. Proposed framework for DMAIC implementation		
DMAIC phase	Purpose	Steps
Define	Describe research problem	<ul style="list-style-type: none"> <li>- CoP formation</li> <li>- Establish Project Charter (study goal, background, project team/formation, Voice of Customer, and schedule)</li> <li>- After Action Review (AAR)</li> </ul>
Measure	Establish baseline performance	<ul style="list-style-type: none"> <li>- Establish metrics</li> <li>- Data collection</li> <li>- Create manufacturing materials flow diagram</li> <li>- Create current-state Value Stream Map (VSM)</li> <li>- After Action Review (AAR)</li> </ul>
Analyse	Identify root causes	<ul style="list-style-type: none"> <li>- Brainstorming</li> <li>- Pareto analysis</li> <li>- Cause and effect diagram (Fishbone diagram)</li> <li>- Material flow analysis (MFA). Assess economic impact of ineffective use of materials</li> <li>- Assess process efficiency and VAA</li> <li>- After Action Review (AAR)</li> </ul>
Improve	Select best solution	<ul style="list-style-type: none"> <li>- Semi-structured interview</li> <li>- Develop potential solutions</li> <li>- Validate potential solution through pilot studies</li> <li>- Improvement performance measurement</li> <li>- After Action Review (AAR)</li> </ul>
Control	Sustain gain	<ul style="list-style-type: none"> <li>- Show the improvement (VSM after improvements)</li> <li>- Assess process stability through X-bar Rchart</li> <li>- Share lessons learnt</li> </ul>

establish the scope of the parameters, as well as their current performance. The metrics established here must be relevant to the industry where the study is being conducted and must be represented on a set of maps so that performance status can be viewed easily.

### 3.3. Analyse

This phase consists of identifying the root causes of poor performance. Therefore, after creating the current material flow diagram and the as-is VSM, the following phase in the proposed approach refers to the analysis and its interpretation for the minimization of the identified wastes and scrap. The first objective of this phase was to enlist the potential defects (and causes); thus, several brainstorming sessions were carried out with the team members. The next objective was to determine, via a Pareto chart, what type of defects were predominant, after which the most relevant CTQs could then be determined. The causes of defects were categorized and prioritized using a Fishbone diagram. As shown so far, the tools and tasks described in this phase are more focused on reducing defects and rejection rates (quality-oriented). Therefore, to analyse the waste in depth, an evaluation of the economic impact of the ineffective use of materials was carried out through a Material Flow Analysis (focused on the occurrence of place and type), as well as a process efficiency study. In line with the literature review, the authors strongly believe that it is easier to identify potential areas for improvement, both to reduce scrap and to significantly reduce waste, by combining these techniques.



### **3.4. Improve**

This phase consists of selecting the best solution with which to solve the root cause, and verifying the improvements applied. First, a semi-structured internal interview with the aim of conducting a session to search for solutions to defects and waste (materials and non-value-added times) had to be defined. The next objective was to develop the potential solutions previously detected. Therefore, the related experiments had to be defined and subsequently applied and validated through pilot studies. Then, the improvement could be definitively introduced into the manufacturing line. Its impact on the overall performance of the manufacturing line should be properly measured using rigorous metrics.

### **3.5. Control**

This phase involves setting up the mechanisms for ongoing monitoring and institutionalizing the improvement actions taken. Establishing a complete VSM after improvements was essential for monitoring and controlling the improvement process. Statistical process control (SPC) tools also helped here. Therefore, in the context of both material consumption and rejection rate (scrap) monitoring, and with the aim of assessing the stability of the process, the most appropriate control charts used through Minitab software were type X-bar R charts. Finally, the formal documenting of all the improvement actions taken and best practices, as suggested by this DMAIC stage, ensures that all employees will now carry out the processes in a uniform manner, which contributes to reducing the variability of the metrics considered (Jamil et al., 2020).

It should be mentioned that the end of each Six Sigma-DMAIC phase was concluded with a review session phase to assess the group's achievements towards the overall organizational goals. The subsequently documented extracted explicit knowledge from each phase after the action review session was then added to the knowledge repository system for easy retrieval and cross-referencing.

Although the present paper aims to establish a well-defined framework based on DMAIC methodology to systematically guide any continuous improvement project within the overall composite industry, the approach proposed here was validated in a manufacturing line of composite padel rackets (see following section for further detail).

## **4. Applying the proposed approach: Results and discussion**

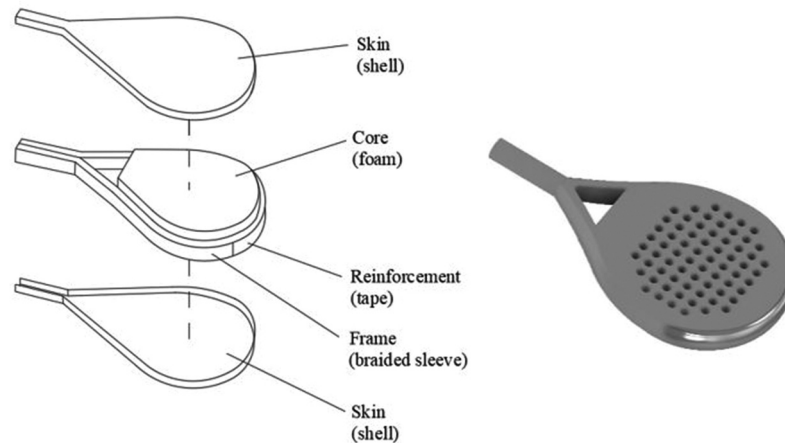
The current project explores a composite padel racket manufacturing line. As a good knowledge of all the steps of the manufacturing process is essential to understanding the main challenges facing padel racket production using composites, a basic description of the product is presented here.

As shown in [Figure 1](#), a padel racket is mainly composed of foam wrapped by a frame and is fully covered with two identical skins. The frame is called a braided sleeve before being solidified through the curing process. This braided sleeve is combined with carbon tape reinforcements to further increase the stiffness of the resulting frame.

*Cell 1: Skin Production.* A padel racket contains two skins that are totally symmetrical to the mid-plane between the two faces. The raw material used is a combination of pre-impregnated carbon fibre (CFRP) and glass fibre (GFRP).

As shown in [Figure 2](#), this manufacturing process is divided into three sub-cells:

**Figure 1. Geometry and scheme of the main parts of a padel racket.**



**1A) Prepreg Cutting.** The pre-impregnated composite material is cut with a metallic cutting-die. The variation of material wastage depends mainly on two factors: (i) the distribution of the nesting in the cutting-die and (ii) the position of the cutting-die in the press machine.

Composite prepreg is extremely expensive. Therefore, wastage must be reduced as much as possible to achieve a cost-effective and sustainable padel racket processing plant that uses composite materials. This is, in fact, one of the biggest challenges because, in many cases, this optimization requires drastic changes to the cutting process, leading to significant investments in machinery.

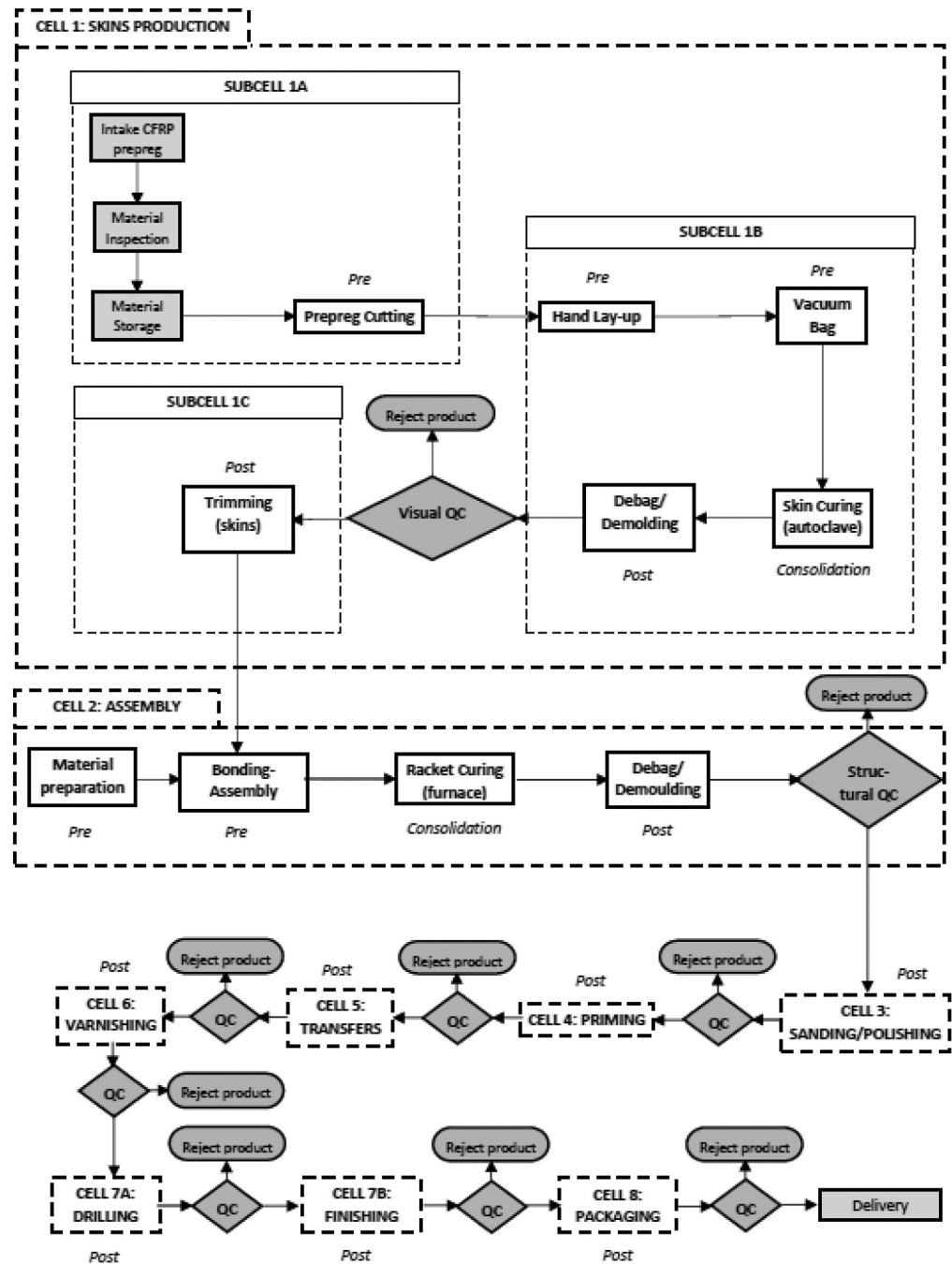
**1B) Prepreg hand lay-up and first curing process.** The previously mentioned plies are laminated by hand over a mould. A lay-up mould corresponds to a single skin and, depending on the autoclave structure and its dimensional limitations, a maximum set of 15 skins can be cured at the same time. Therefore, the 15 laminated moulds must be deposited on a sandwich structure and the vacuum bag prepared to be cured in the autoclave for 180 minutes (i.e., by applying high temperature and external pressure). A total of 30 lay-up moulds are required for an adequate mould rotation.

A key part of the final performance of the padel racket depends directly on the manufacturing process of the skins. Therefore, in this sub-cell the challenges that arise are diverse and of the utmost importance, i.e., (a) minimize manufacturing defects, mainly external porosity that commonly appear in 3D geometries such as skins, (b) reduce the variability of the lay-up process, which is a completely manual operation. Nowadays, the appearance of a composite padel racket depends largely on the laminator experience, and the consumer demands a carbon fibre weave that looks flawless on the padel racket, (c) minimize the curing time because the autoclave is a significant bottleneck in the entire manufacturing process, and (d) reduce the risk of curing large batches in the same cycle.

**1C) Trimming skins.** The skins are trimmed on a plane parallel to the impact surface through a CNC machine.

**Cell 2: Assembly and second curing process.** The resin mixture is uniformly impregnated throughout the braided sleeve, the tape, and the inner part of both pre-cured skins. The wet lay-up process continues with the centring of the foam on the skins. The braided sleeve and its plastic tubular

Figure 2. Flowchart of main production processes for a padel racket.



inside are also located around the core. The product is then placed into a closed-symmetric mould, and cured for 50 minutes in an oven, while the plastic tube inside the braided sleeve is constantly inflated with pressurized air to reach a correct bond to core and skins. Both parts of the mould will fit perfectly if the skin trimming operation is accurate. As there are six curing stations working in parallel, a total of 12 assembly moulds are available to maintain adequate mould rotation.

The main challenge for this workstation is to avoid air gaps or poor adhesion between braid and skins, otherwise this defect will lead to weak spots which could lead to impact failure. The operations performed lead to a bottleneck; albeit not the most relevant bottleneck in the whole process.

*Cell 3: Sanding and polishing (aesthetic).* The small gap between the skins and tiny superficial defects are filled with a specific putty. The mixture cures at room temperature for one hour and then a completely uniform and smooth surface is obtained by sanding and polishing. The bottleneck in this cell is one of the most important in the production process as the processing time here greatly depends on the quality of the product in both previous cells, repeatedly leading to multiple reworks.

*Cell 4: Primer coating (aesthetic).* The primer coat is applied manually with a paint gun and is dried for two hours in an oven.

*Cell 5: Transfers (aesthetic).* The decals are applied to both surfaces of the padel racket using a transfer film and then the drawings are oven dried for 20 minutes.

*Cell 6: Varnished (aesthetic).* The padel rackets are manually varnished with a painting gun. Twelve-hour dries are performed at night (out of working hours) to optimize resources and avoid a more significant bottleneck.

*Cell 7: Finishing (aesthetic).* Divided into two sub-cells: (a) hole machining, where padel racket holes are drilled by a CNC machine; and (b) handgrip details, where protector, grip and cord are manually added to the product.

#### **4.1. Define phase**

The manufacturer of the composite materials used in this study, set up a production plant for padel rackets two years ago but revealed that it has never been as profitable as had been anticipated. A previous market feasibility study confirmed the sale price was fair and competitive, and so increasing the price to cover costs was not an option that could have been considered. The problem, therefore, was in the production costs; even though the manufacturer felt the costs had been correctly valued (two years ago). These imbalances, then, are predicted to come from production line inefficiencies (material consumption and time).

The technicians and managers from the manufacturing company, albeit through scarce historical data, highlighted an internal rejection rate of around 15% for each of the first two cells, and 31% in the entire manufacturing process, showing that there was indeed a significant problem with quality. This is particularly alarming because the highest rejection rates were found in the first two cells in which it is understood that the manufacturer, with their extensive experience in composite materials, offers the greatest added value to the customer. Furthermore, while the manufacturer also firmly believed that the wastage of the composites and internal rework was currently too high, there were no metrics available in this regard. Finally, the company had detected an 8% external rejection rate due to weak areas of low resistance that cause premature breakage on impact. This rejection rate is significant as it is not only the source of profit reduction, but is also creating customer dissatisfaction.

**Table 2** shows the DMAIC project charter developed as a working document to solve the problems described above.

**Table 2. Project charter for manufacturing composite padel rackets**

**Background and reason for selecting the project:** Based on historical data, the internal annual rejection rate of the manufacturing process is recorded as 31% (divided as follows: skin production 15%; assembly 15%; 1% between cells 3 and 8). The external rejection rate is recorded as 8% due to weak areas of low resistance that cause premature breakage on impact. Based on qualitative data (interviews and discussion with personnel), the composite material wastage and time (internal rework) is currently too high, predictably out of budget. Overall, this is resulting in loss of revenue and lower customer satisfaction.

**Study goals and expected benefits:** (a) reduce the internal rejection rate to at least 5% for the skin production and assembly cells; (b) eliminate the external rejection rate by identifying the root cause of the problem in low resistance areas and establishing effective methods to detect it internally; (c) identify, understand, quantify and reduce the waste (both composite materials and non-value-added times). Wastage exceeding 25% in carbon fibre raw materials is alarming and should be reduced immediately. This would result in significant cost savings, more sustainable manufacturing, higher throughput of the entire process, and increased customer satisfaction.

**Project team/formation:** A cross-functional team was formed consisting of the operators (at least one responsible per each cell), production engineers, quality, and senior managers. This team spent many hours on the shop floor observing in order to collect data and understand the different processes associated with the manufacturing of composite padel rackets. At the project's inception, the production manager and continuous improvement engineers received specific training on the Six Sigma-DMAIC and VSM approach applied to the real case of padel rackets. This training was given by an external consultant with extensive expertise in the application of the tools (in other sectors) involved in this study.

**Voice of Customer:** During problem identification, several brainstorming sessions with the team members were conducted to identify critical to quality (CTQ) characteristics based on the voice of customer (VOC) input. Most customer complaints are related to padel rackets with weak areas of low resistance that are causing premature breakage through impact (the main reason for the 8% external rejection rate). According to the customer, the most critical factor is quality, not delivery time. It was also decided that customer remarks about padel rackets having minimal aesthetic defects (micro-porosity, open gaps, or incomplete filling) would be immediately rejected. Finally, the customer specifies the need to maintain the type of raw material used so far, thus future improvements should focus on methods and processes.

**Schedule/Implementation plan:**

<i>Define</i>	<i>Measure</i>	<i>Analyze</i>	<i>Improve</i>	<i>Control</i>
<b>Three weeks</b>	<b>Four weeks</b>	<b>Four weeks</b>	<b>Nine weeks</b>	<b>Two weeks</b>

#### 4.2. Measure phase

The manufacturer involved had been collecting data on rejection rates per cell for the last two years and had identified the critical processes where maximum defects were occurring, but no relevant action had yet been taken. The project team—divided into small groups—decided that to validate the historical data they had, they would collect defective product data from their respective workstations over the following 28 days of production.

As shown throughout this section, the data collected were analysed and the rejection rates from the recently collected data were found to be slightly higher than those from the historical data. The quality metrics were an 18.3% rejection rate for skin production (cell 1) and 18% for assembly (cell 2). In the case of cells 3 and 8, the rejection rate was 0.8%, i.e., very close to the historical data. Therefore, the highest number of defects it was confirmed to occur in the first two cells. Related to other essential metrics such as consumption and composite material wastage, there were no historical data, thus, this was collected for the first time over the 28 day period. Likewise for process times, which were obtained by time study. The measurements are shown below.

##### 4.2.1. Waste of composite material and quality

The square metres of composite material provided by the prepreg manufacturer are known, as well as the area of the lay-up plies for the skins (according to the cut nesting). Therefore, the prepreg wastage in cell 1A is known by counting the plies per roll obtained. This procedure is performed by different operators to confirm that the human factor does not significantly influence the waste due

to the variable positioning of the manual die in the press. The 29% waste value remained stable over the 28 days (Table 3).

CoFRP (prepreg) waste must be measured as it is processed through the various serial operations. In the “Waste” column in Table 3, operation number 2 does not entail a loss of prepreg, but operation 3 does imply a 16% loss because the skins are a Near Net Shape (NNS). It is not possible to obtain net skins after curing, these skins must go through the trimming process, which involves a composite residue that needs to be considered. Therefore, maintaining a prepreg margin outside the nominal area during the lay-up process is a must. Despite this, there are options to reduce this waste if needed. For instance, the operator could centre the prepreg plies with greater precision by making a mark engraved on the same laminate mould (outside of nominal area), which allow the prepreg margin to be reduced, hence optimizing the nesting.

As shown in Table 3, the sum between waste and scrap values results in the non-effective use percentage of the prepreg material for each operation. When applying these values, it was observed that just 47.3% of the pre-impregnated carbon fibre is being used effectively. Therefore, from a 100 sqm prepreg roll, only 119 rackets are effectively manufactured up to the quality control of cell 2 (each racket contains 0.3976 sqm of prepreg). The consequences of this low value will be analysed in depth in Section 4.3.

The same procedure was followed for the rest of materials, both raw and auxiliary, used for manufacturing, for each workstation. At cell 2, EVA foam sustains 27% permanent waste, while an average waste of 30% was determined for the manual mixing of resin and hardener associated to the wet lay-up process. The braided sleeve and tape were recorded as zero waste, but 18% of the scrap in Table 3 must also be considered in order to obtain the ineffective use of raw material from cell 2 (i.e., materials already assembled on rejected rackets). Finally, the waste and scrap for cells from 3 to 8 are negligible because the resulting ratios were around 0.2% per workstation.

After gathering all the necessary data, this was then displayed in a visual flowchart from which the engineers could easily control the status of the manufacturing materials, as shown in Figure 3, for working cells 1 and 2. The manager of each working cell registers the data recorded daily and this is automatically linked to the program database (Table 3) and to the representative flowchart. For each operation the input and output materials are displayed automatically by introducing the actual waste and scrap values.

Figure 3 represents the evolution of the main raw material through the different transformation processes (blue diagrams). The width of the blocks is proportional to the amount that remains after applying the rejection rate and the waste percentage for each process. The type of rejection for each process is also indicated. The orange diagrams represent the input of other raw materials corresponding to cell 2, and the input material values shown are the minimum required to feed the streamline. The simple arrows likewise represent the auxiliary materials. Using this tool, it is also easier to make an adjusted forecast of stocks by applying the corrective factors from waste and scrap.

#### 4.2.2. Time study and efficiency

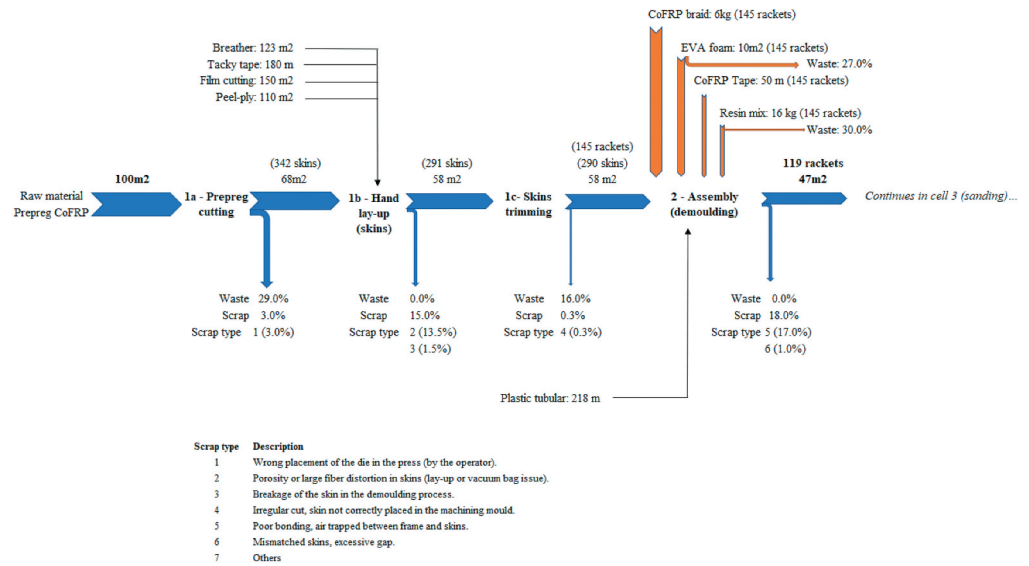
The cycle time per workstation must be quantified and based on the resulting values, the rework times can be estimated. As shown in Table 4, the total time per cell may not be equal to the total added value (operator and machine). On the one hand, taking the criteria described in Section 2.2 as the reference, the curing of the composite materials (cells 1 and 2) are value-adding activities because this is a specialized process that results in better mechanical properties. On the other hand, the drying procedure performed in the subsequent cells is considered non-value-added-but-necessary times and involves the following items: putty (C3), primer (C4), decals (C5) and varnish (C6). Furthermore, the



**Table 3. Real utilization of CFRP prepreg raw material. The conversions between square metres and produced units have been made according to the cut nesting**

Operation	Description	Units	Material Input	CFRP Waste	Local Scrap	Non-effective use	Material Output (Real Use of CFRP)
1	Cell 1a: Prepreg cutting	m2	100	29.0%	3.0%	32.0%	68 (68.0%)
2	Cell 1b: Lamination and curing (Quality Control)	skins	342	0.0%	15.0%	15.0%	291 (85.0%)
3	Cell 1c: Skin trimming	m2	58	16.0%	0.3%	0.3%	58 (98.8%)
4	Cell 2: Assembly and curing	rackets	145	0.0%	0.0%	0.0%	145 (100.0%)
5	Cell 2: Demoulding (Quality Control)	rackets	145	0.0%	18.0%	18.0%	119 (82.0%)
-	TOTAL (up to cell 2)	rackets	-	-	-	-	119 <b>(47.3%)</b>

**Figure 3. Manufacturing materials flow diagram for work cells 1 and 2.**



period that a product is in a machine does not always generate added value. For instance, drilling a racket would be an added value but the time that the product is in the cooling station before releasing the racket from the mould without undergoing any transformation is clearly a non-added value.

From Table 4, note that the operator’s processing time only represents 7.4% of the total process time (dividing total time VA operator and total time per cell, both in seconds). The machinery processing time accounts for the remaining 92.6% (adding VA and NVAN machine times and dividing the result by the total time per cell, both in seconds). Only 20% of machine time is added value (dividing the VA of machine time by the total sum of machine time). These data will be analysed in depth in Section 4.3.

To gain insight into the initial current state of padel racket manufacturing, a value stream map (VSM) was developed (see, Figure 4), providing a closer look at the process so that any opportunities for improvement can be identified. Below each process, cycle time (CT), machine uptime (U/T), the number of shifts, and the changeover time (C/O) are listed. The scrap percentages are linked to those shown in Figure 3. The number of shifts in this case corresponds to the active hours of operator per process, considering that a shift is eight hours. There are eleven operators working eight hours a day for five days a week.

During the development of the VSM, it was found that the value-added time was low (see, Figure 4). Additionally, it is observed that the changeover time (CO) is generally notably higher than CT in common cells where the mechanical capacities of composite materials are not transformed (sanding, priming, transfer and varnishing), so it is expected to have a very negative impact on the overall production line efficiency.

### 4.3. Analyse phase

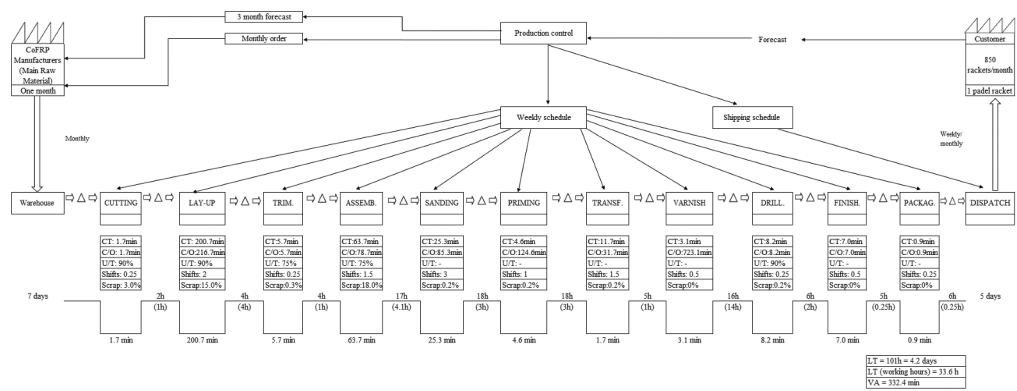
#### 4.3.1. Defects and quality

The defect rate (scrap) was unacceptable for workstations, skin production and assembly. Therefore, the goal of the team members was to identify the root causes and significant process

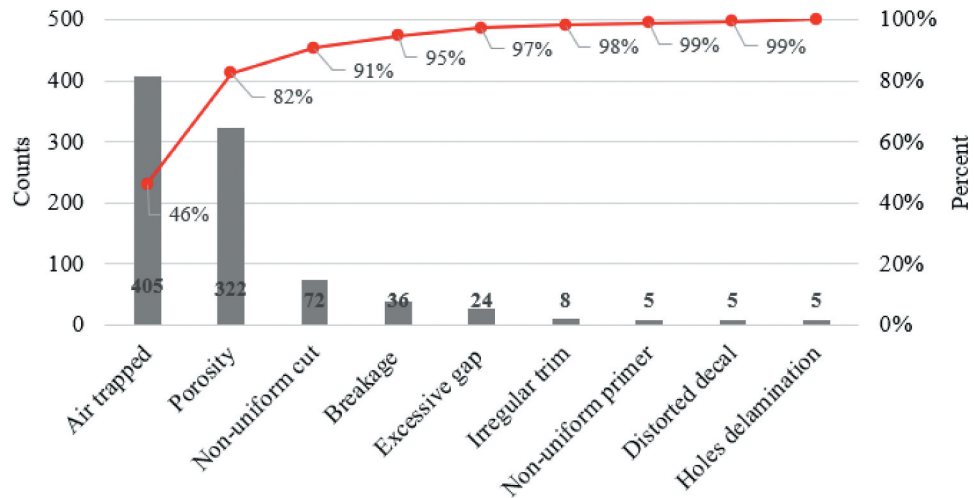
**Table 4.** Cycle times (operator, machine and total) for each cell. The machine time for the cutting operation is zero because the machine does not work by itself but is always operated. Therefore, this time is already associated with the operator

	Operator time			Machine time			Total time	
	VA main task (s)	VA support task (s)	Total VA (s)	VA (s)	NVAN (s)	Per cell (min)	VA operator & machine (min)	
C1a: CUTTING	86.9	14.2	101.0	0.0	0.0	1.7	1.7	
C1b: LAMINATION	580.0	662.0	1242.0	10,800.0	962.5	216.7	200.7	
C1c: TRIMMING	60.0	140.0	200.0	140.0	0.0	5.7	5.7	
C2: ASSEMBLY	630.0	310.0	940.0	2880.0	900.0	78.7	63.7	
C3: SANDING	1357.0	158.0	1515.0	0.0	3600.0	85.3	25.3	
C4: PRIMING	220.0	545	274.5	0.0	7200.0	124.6	4.6	
C5: TRANSFERS	460.0	242.0	702.0	0.0	1200.0	31.7	11.7	
C6: VARNISHING	167.0	19.0	186.0	0.0	43,200.0	723.1	3.1	
C7a: DRILLING	12.0	31.0	43.0	450.0	0.0	8.2	8.2	
C7b: FINISHING	360.0	60.0	420.0	0.0	0.0	7.0	7.0	
C8: PACKAGING	20.0	330	53.0	0.0	0.0	0.9	0.9	
TOTAL	3952.9	1723.7	5676.5	14,270.0	57,062.5	1283.5	332.4	

**Figure 4. Value stream map (before improvements) after 28 days of sampling (average values).**



**Figure 5. Pareto chart for type of defect, after 28 days of sampling (average values).**

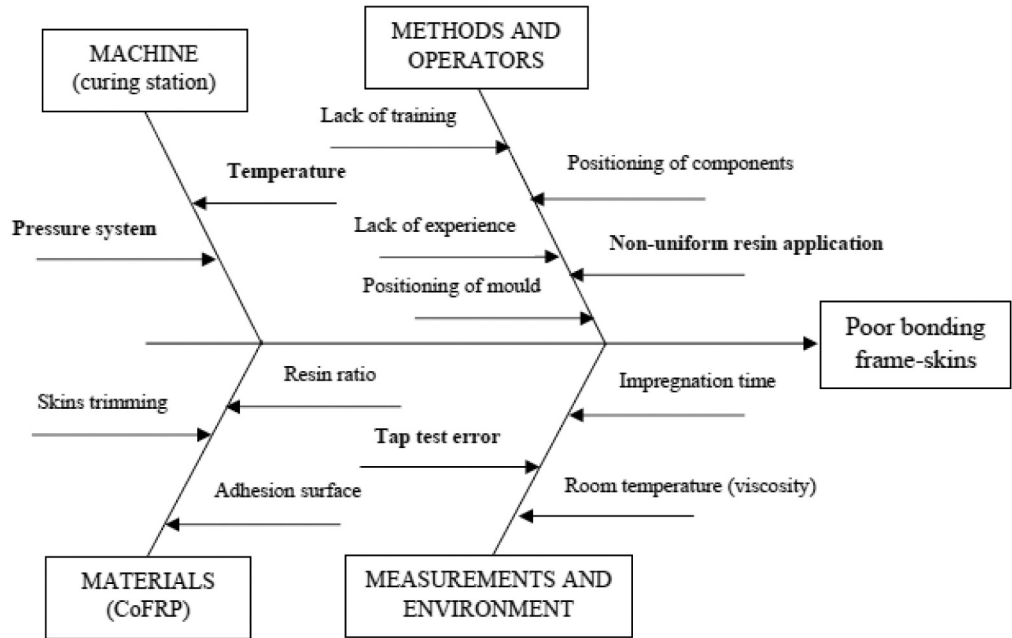


parameters that were causing the predominant defects. After conducting several brainstorming sessions, the group concluded that the trapped air matter was a result of poor bonding and the unique cause of the low impact resistance spots along the perimeter of the padel racket that was causing 17% of internal rejection in cell 2 and 8% of the total external rejection. The Pareto chart shown in Figure 5 illustrates the contribution of defects in the process in percentages. The Pareto principle is fulfilled because roughly 80% of the defects come from 20% of the causes. Subsequently, it can be concluded that the critical quality characteristics are trapped air (cell 2) and porosity (cell 1). The porosity defect means a rejection rate of 13.5%. Therefore, efforts to improve processes should focus on reducing both of these defects.

To categorize the possible causes that affect the bonding between the frame and the skins, a cause-and-effect diagram was developed (see, Figure 6).

The cause-and-effect diagram shows that the most important process parameters that affect frame-skins bonding are inflation pressure of the tubular inside, temperature distribution throughout the product, and non-uniform application of resin. Errors in the tap test led to the client receiving defective rackets (direct influence on the external rejection rate).

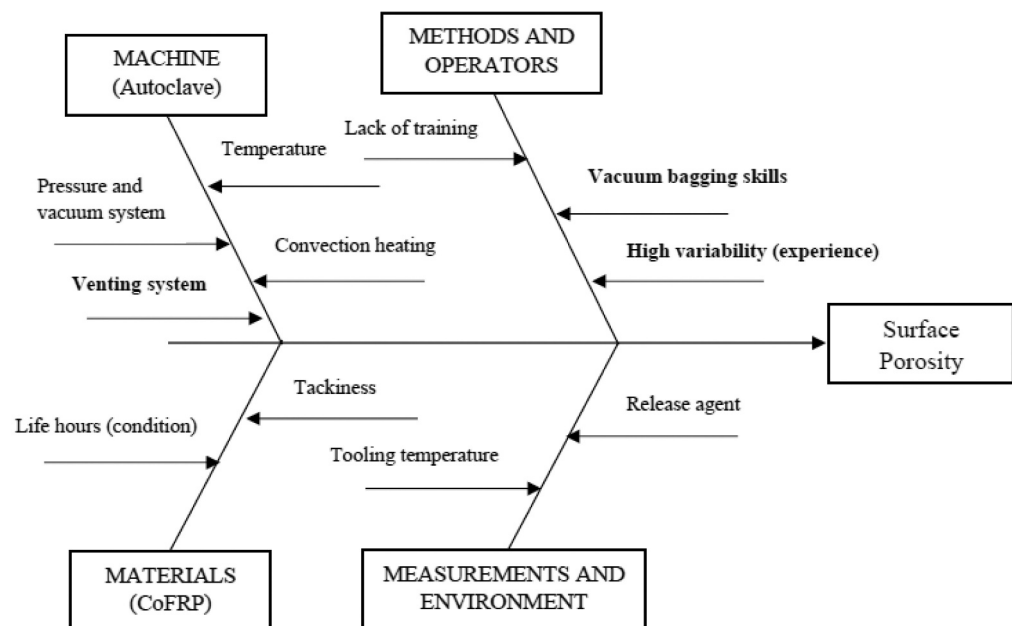
**Figure 6. Cause-and-effect diagram for the poor bonding issue.**



The same procedure was followed for the porosity problem (Figure 7).

The cause-and-effect diagram shows that the most important process parameters that affect skins porosity are vacuum bag ventilation system in autoclave (outgassing) and the variability

**Figure 7. Cause-and-effect diagram for porosity issue.**



**Table 5. Materials and cost per racket for each workstation**

Cell	Type of material	Cost per type of material (%)	Totals cost of material per cell (%)
1	Raw material	30.85	39.40
	Auxiliary material	8.55	
2	Raw material	22.33	23.17
	Auxiliary material	0.84	
3	Auxiliary material	3.13	3.13
4	Raw material	4.08	4.61
	Auxiliary material	0.52	
5	Raw material	10.31	10.31
6	Raw material	4.26	4.78
	Auxiliary material	0.52	
7	Raw material	5.13	7.36
	Auxiliary material	2.23	
8	Raw material	7.24	7.24

according to the experience of the operators, either during the lay-up process or during the bagging process.

#### 4.3.2. Material consumption and waste

Table 5 details the manufacturing materials by workstation as well as their associated market cost. Through these data, the cost of materials for each cell, differentiating between raw material (BOM material) and auxiliary material (production cost), can be extracted.

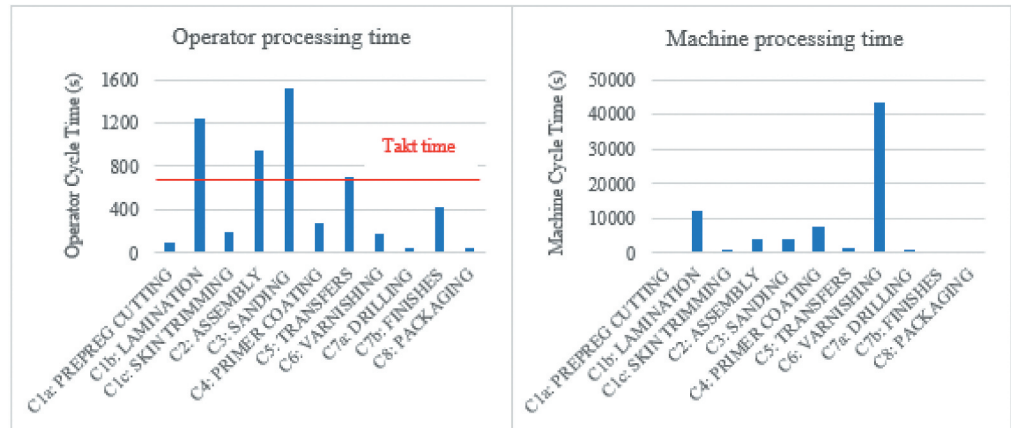
As shown in Table 5, the material costs for workstations 1 and 2 represent 62.57% of the total cost required to manufacture a padel racket. In this scenario, a possible cost deviation in these two working cells would represent an extremely negative impact on the profits of the project due to a high extra cost not initially anticipated. The cost per racket related to raw material in cell 1 is initially 30.85% of the total cost, and the only raw material in this cell is CoFRP prepreg. Based on the results shown in Table 3, the real prepreg use percentage was 47.3%, noting that the prepreg waste was 45%. This value is unacceptable as it exceeds the typical budgets for carbon fibre products whose margin for prepreg waste is up to 25%.

**Table 6. Increase in unit costs due to waste and scrap for raw materials in cell 2**

Raw material cell 2	Total waste	Total Scrap	Unit cost increase
EVA foam	27%	18%	+45%
CFRP braided sleeve	0%	18%	+18%
CFRP tape	0%	18%	+18%
Epoxy Resin	30%	18%	+48%



**Figure 8. Left: Operator processing time. Right: Machine processing time.**



The following procedure has been used to calculate the deviations for the raw materials of cell 2.

In Table 6, the unit cost increase is directly proportional to the ineffective use of the raw materials due to the waste and the scrap quantified in the previous section. Although the cost of CFRP is higher in cell 1 than in cell 2,—30.85% versus 18.19%—(not 22.23% from Table 5 because the foam is not CFRP), the 18% cost increase in cell 2 is significant enough and the scrap must be reduced to make racket production affordable. In contrast, the waste from this workstation has little impact on the total cost of manufacture, and as the waste of EVA foam and epoxy resin (about 25%) are typical values, these have already been considered in the budget. As a summary, during the development of the current analysis it was confirmed that the waste rate for cell 1, which is mainly dominated by the composite prepreg, was unacceptable.

#### 4.3.3. Process efficiency and value-added analysis

Taking the previous time study as well as the defined VSM as a reference, the operator processing time was very low (7.4%) in comparison to the machine processing time (92.6%). Such a high percentage of machine processing is mainly due to long oven cure cycles (drying of non-value-added-but-necessary at workstations 3 to 6). Therefore, it is important to note that this value does not mean that the production line is highly automated.

As seen in Figure 8 on the right, the machine processing time of cell 6 (varnishing) is notable. Despite this, as delivery time is not a critical factor for the customer this activity is defined by the manufacturer as a low value-added support workstation. Therefore, it is not the aim of this study to reduce this time interval. Relatively large operator times in cell 1, along with machine times (due to the autoclave cure cycle) were also detected. Therefore, it is important to dedicate efforts towards optimizing primarily the lay-up process and its cure cycle.

In Figure 8, the takt time is calculated considering that the client estimates receiving 213 rackets per week (850 per month), and assuming that the workflow will be constant through the production line. Dividing the 40 hours of weekly work by the 213 rackets, the average time between the start of production of each unit should be 11.3 minutes, which corresponds to the takt time and without considering interruptions bound to happen such as machine downtime and scheduled employee breaks. Based on the results, it is observed that the entire manufacturing process is unable to work at the rate established by the takt time (Figure 8 left, the takt time bar should be above all cycle time columns). Therefore, it would be convenient to modify the quantity being demanded, the resources, or to redesign the production process affected (mainly in cells 1b, 2 and 3).

From the data in Table 4, the Line Balance Ratio (LBR) is calculated and results in only 34.1%. The total net time of all processes (5676.5 seconds) is divided by the longest process time (1515.0 seconds) and multiplied by the total number of workers involved. The LBR value indicates that the production line is highly unbalanced between cells which, in turn, facilitates the appearance of bottlenecks. As shown in Figure 8 on the left, the sanding cell has the longest operator processing time, thus more manual labour should be employed there or the process time should be significantly reduced, otherwise this will lead to a significant bottleneck.

Furthermore, it is known that a padel racket is completed in 33.6 working hours (real lead time value). Value-added time for operators (5676.5 seconds from Table 4) divided by the actual lead time results in a process cycle efficiency (PCE) of 4.7%. A PCE lower than 5% indicates that the efficiency of the process needs to improve because typical values are on the threshold of 5–10% (Karabay & Kansul, 2019).

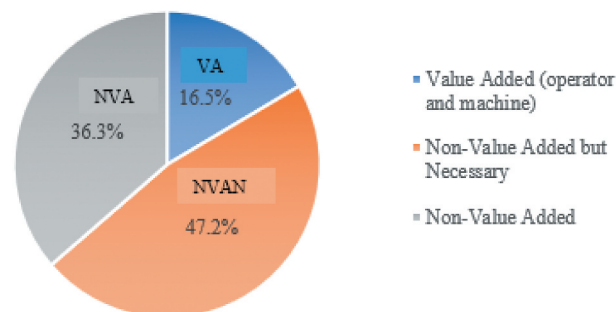
From Table 4, it was observed that the sum of all cycle times recorded separately (operator and machine) resulted in 21.39 hours of work. The vast difference between the lead time and the sum of cycle times affirms that the workflow is not continuous throughout the production line. This difference of 12.21 hours is due to product waiting times, worker breaks, product transport, queue time, and interruptions (either breakdowns or maintenance). However, through qualitative data it is detected that the main causes are really due to rework tasks and unexpected inspections of defects, also defined as non-value-added activities, likewise indicating that the processes may not be adequate or that the methods are in a low level of maturity (i.e., still on the learning curve). As a result, and taking as reference the total VA (332.4 min) and the total NVAN (951 min) from Table 4 along with the real lead time (33.6 working hours), the difference is calculated as an NVA of 732.6 min. This is shown in percentages in Figure 9.

As shown in Figure 9, only 16.5% of the entire manufacturing processes generate added value. The high activity without-added-but-necessary value is noteworthy. According to the values presented in Table 4, 96.7% of the NVAN activities are found in cells 3 to 6 due to long drying times.

#### 4.4. Improve phase

In the improvement phase, the project team decided to develop solutions for workstations 1 and 2 because the potential opportunities for improvement there were the most relevant in terms of reduction of waste and defects.

**Figure 9. Comparison between VA, NVA and NVAN times in the production line.**



#### **4.5. Improvement 1. Digital cutting machine investment for workstation 1A**

The main goal of this improvement was to reduce the waste of prepreg composite material (a high 29%) to minimum values. Therefore, the cross-functional team decided the best option for optimizing prepreg cutting was to change the die-cutting press for an automated digital cutting machine and its implemented software. Consequently, the waste will no longer depend on cutting die design or manual die placement on the press. As a result of this investment, scrap values dropped from 3% to 1%, and waste from 29% to 8%, thus generating a 7% saving on the total cost of the racket material. According to the software, this new waste value cannot be optimized any further. Thus, the minimum prepreg waste has been included in the budget for the upcoming year.

Furthermore, cutting time has been decreased significantly, and quality has been improved due to the new finer cut. Now the operator and machine work independently, instead of the operator steering the machine for each cutting cycle. Therefore, cycle times have improved as follows: from the previous 101 seconds of prepreg cut per racket assigned to the VA operator, they are now spread over 40 seconds of operator VA and 26 seconds of machine VA. This represents a 23.5% reduction in total cutting time. The cutting support tasks are the same as before, but now the operator is just performing a straightforward setup on the digital cutting machine, as well as picking up and placing the plies. Working in large batches allows the operator to perform other tasks while the machine is running.

#### **4.6. Improvement 2. Semi-automatic lay-up for workstation 1B**

The main objective of this improvement was to reduce the variability resulting from the hand lay-up process as well as reduce operator cycle time during the lay-up process. The variability in the manufacture of the skins means that a totally standard product is not obtained. Therefore, the functional team decided to implement semi-automatic lamination using a pneumatic press already available in the workshop, which led to the manufacture of a set of hard silicone counter-moulds, one for each skin lay-up mould. Now the procedure is as follows: the operator places the prepreg ply (2D shape) on top of the lay-up mould, and slightly adjusts the silicone counter-mould on the prepreg layer. The assembly is then fed into the two-plate press and the machine compresses the positive counter-mould into the negative mould, leading to laminating the skin in just 15 seconds (3D shape). This new system has a moderate margin of error due to its automatic centring. As such, the team decided not to modify the cut nesting of prepreg layers. As a result, the waste at the skin trimming workstation remains at 16%. Now, however, the total operator time cycle for sub-cell 1B is 862 seconds instead of the initial 1242 seconds, which represents a 30.5% reduction in lamination time. In addition, the skins are always laminated with the same pressure.

#### **4.7. Improvement 3. Press hot forming for workstation 1B**

The aim here was to reduce the reject rate from 15% to at least 5% at the skin production workstation. The porosity defect was the dominant factor in this rejection, (the causes of which have been analysed in the previous section). Based on these, the engineers decided that the best option was to replace autoclave curing with hot forming curing. The reduction in machine time was also a key factor in taking the final decision on the matter.

Implementing the hot forming curing process was possible because the prepreg material used is also suitable for out-of-autoclave (OoA) curing. The new curing process is very similar to the semi-automated lamination of the previous point but with two main differences: (a) the press must be hydraulic to apply high pressure during curing; and (b) this press requires hot plates to cure at high temperatures while the pressure is applied. The silicone counter-mould system is robust enough to repeatedly withstand a pressure of 30 Tonnes at 150°C for 23 minutes, which is the optimal setup defined through several pilot tests.

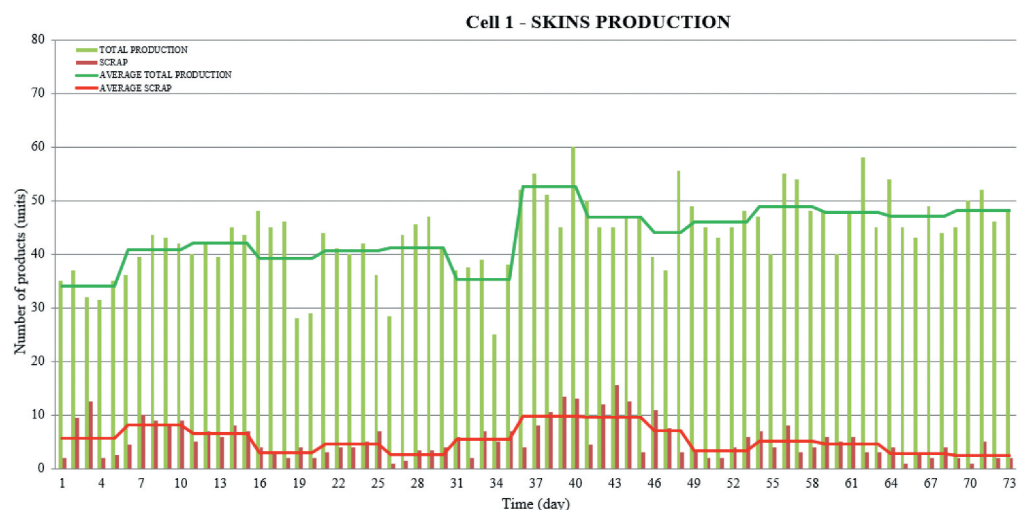
Replacing the autoclave with a hot forming press directly means removing the vacuum bag preparation process. Consequently, the main cause of porosity has been eliminated, as well as removing the handling of a heavy structure in the autoclave and the subsequent debugging process. Therefore, beyond the benefits in terms of health and safety, and environment (HSE), this represents a total reduction in operator time of 58%, while the total cost of materials per racket drops another 3.5% because the rejection rate is reduced to 6% instead of 15%. Another notable advantage is the elimination of the risk involved in curing batches of 15 skins in the same vacuum bag.

Figure 10 shows the evolution of daily production and scrap at the skin manufacturing workstation. Prior to day 5, the metrics were highly stable because the analysis phase was still in progress in the workshop. From day 5 onwards, the improvements described at this point were applied progressively. Until day 65, the pilot tests were carried out within the improvement phase, subsequently leading to the control phase. Therefore, the autoclave curing corresponds to days 1 to 5. Starting on day 6, hot press curing was introduced, and it was observed that the average production increases from 35 to 40 rackets per day. This is due to the reduction in operator time when removing the vacuum bag from the process.

As shown in Figure 10, the new curing process implemented by compression press results in a 5% increase in scrap (from day 6 to day 15). This was to be expected as it is widely known that the hot forming method can easily lead to fibre distortion and increased porosity. However, it was unacceptable to increase the number of skins produced if this meant increasing the rejection rate. Therefore, before employing this new process on the production line itself, the cross-function team decided to conduct further pilot tests focused on variables such as pressure, time, and temperature to achieve a robust process. From day 20, hot forming re-enters the production line because the process is sufficiently stable following the out-of-production tests. In the days of absence of hot forming, the total production did not drop significantly thanks to the improvement in the semi-automatic lamination with press.

The change from an autoclave to the hot forming press reduced the curing cycle time from 180 minutes to 23 minutes. Nevertheless, it should be emphasized that in the autoclave 15 skins were cured at the same time in 180 minutes, (i.e. one skin cured every 12 minutes), whereas now

Figure 10. Evolution of total production and scrap per day in cell 1B. Production of rackets on the Y-axis. A racket contains two skins.



in the hot press the cure cycle is 23 minutes, but the capacity is only two skins on the available hydraulic press. This resulted in a skin cured every 11.5 minutes; a production rate very similar to the previous one by autoclave curing. Therefore, from day 35 onwards, an investment was made in a larger area press machine that allows five moulds (instead of two) to be cured at the same time. This means a cure cycle of 4.6 minutes per skin instead of 11.5 minutes with the previous press. As shown in Figure 10, this also means temporary losses due to the learning curve of a new equipment (from day 37 to day 47).

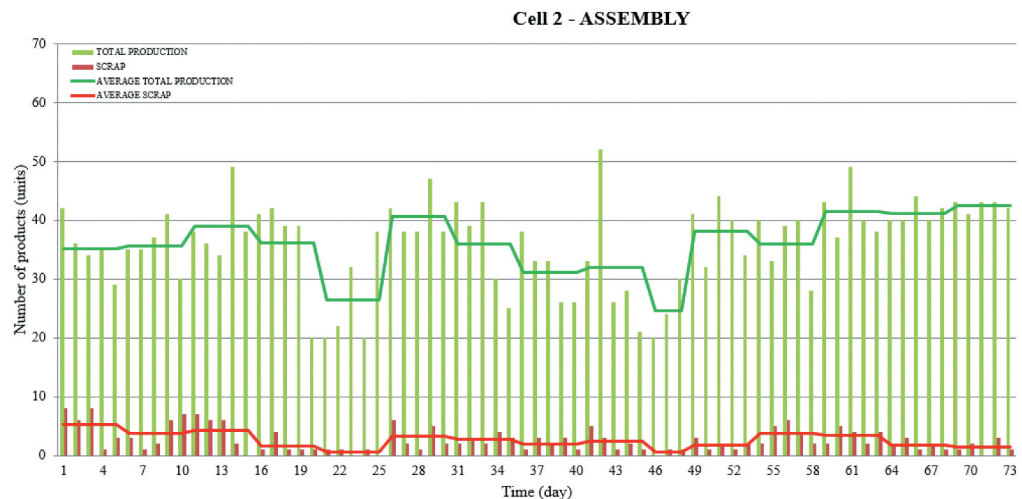
During this period, the engineers discovered that the flatness of both compression surfaces is a key factor in producing products without defects (and reducing the scrap), as well as a uniform distribution of pressure and temperature in the five moulds. Another key point was to determine the appropriate moment to apply the compressive pressure by considering the resin rheology. As of day 61, production in cell 1 tends to stabilize at around 47 rackets (94 skins) per day, with a scrap of approximately 6%.

#### 4.8. Improvement 4. Exhaustive review of equipment and processes for workstation 2

The goal of the improvement described above was to reduce the internal reject rate from 18% to at least 5% at the assembly workstation. It was unacceptable that defects in critical to quality (CTQ) characteristics had not been detected internally. The poor bonding defect was the dominant factor for both rejection types. That said, material waste was not an issue here. The machine time was already adequate and workstation 2 did not cause any notable imbalances in the production line. Therefore, the wet lay-up process has been optimized, rather than changed. This entails more control of the process variables, standardized tasks, recurrent structural controls, and exhaustive daily monitoring.

Pressure tests on tubular inflation for braided sleeve and thermal mapping were performed to measure the distribution of pressure and heat exerted on the product throughout the curing process. Both tests described provided key data for determining the optimal parameters with which to minimize the poor bonding defect. As such, several thermocouples were installed on the assembly moulds along with some pressure regulators at strategic points on the feed line. The main goal was to control these key parameters on a recurring basis. As a result, scrap was reduced to 5%, which means an 8% savings in material costs per racket, and the production of rackets in

Figure 11. Evolution of total production and scrap per day at workstation 2 (assembly).



the assembly step appears to stabilize from day 59 with the scrap percentage remaining low (see, Figure 11).

Another cause of poor adhesion was non-uniform application of resin. The team studied the possible automation of this process, but this was ultimately discarded due to lack of funding. Despite this, several one-point lessons were programmed that aimed so that all the operators would apply the resin in the same way, regardless of their experience. Finally, to detect all faulty padel rackets due to internally trapped air, the engineers proposed a double tap test (in cells 2 and 3) because, through some interviews conducted with the operators, it had been discovered that the size and shape of the resin claps along the perimeter of the rackets influenced the sound of the hit during the tap test, easily leading to erroneous quality decisions. Therefore, once the padel racket leaves workstation 3 it is easier to detect any structural defects because the racket is completely clean. The double tap test means a 30-second increase in operator time at the sanding workstation. The team decided to maintain this test as it is widely validated by the composites industry. The result for this workstation is that the external rejection rate has dropped from 8% to 0.3%.

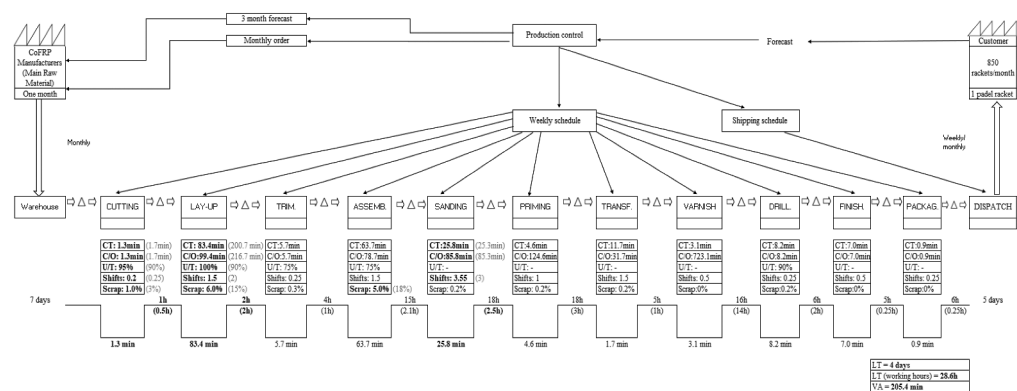
As in the production skin workstation, Figure 11 shows that before day 5 the metrics were highly stable because of the analysis phase was still in progress in the workshop. From days 5 to 65, engineers were carrying out various pressure tests and thermal mappings, hence the high irregularity in production.

#### 4.9. Control phase

At this last stage, a new VSM shows the level of improvement attained after the study of the previous phase. The assembly workstation requires exhaustive monitoring because it has been demonstrated that proper control of the poor bonding defect is critical within the padel racket manufacturing process. Therefore, a X-bar R chart chart is used to monitoring the scrap at cell 2.

Figure 12 shows the value stream map after improvements. Current values which changed from the VSM of the measurement phase (Figure 4) are represented in bold, while old values are displayed on the right side of the data boxes. On the one hand, it can be observed that in cell 2 there is no higher performance in terms of time consumption. On the other hand, the improvements made in the cutting and lay-up cells (i.e., beyond significantly reducing scrap), represent a remarkable reduction in production times (23.5% and 41.6%, respectively) which, in turn, allows operator hours to be moved to bottleneck-prone areas, such as the sanding workstation. In this cell, the cycle time increases slightly due to the introduction of the double tap test. In addition, the

**Figure 12. Value stream map after improvements, 14 days of sampling (average values).**





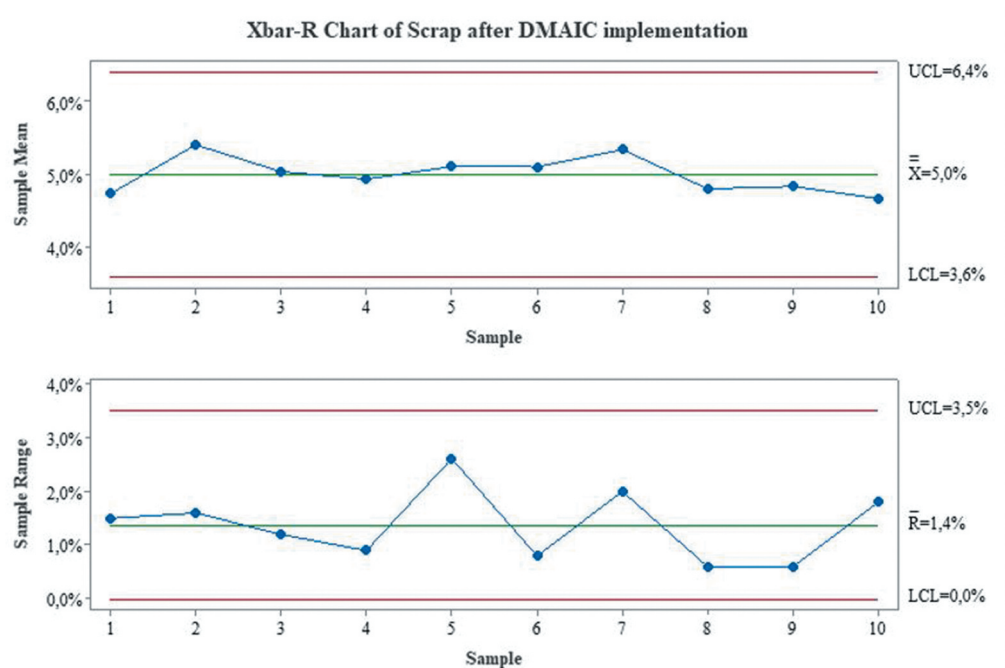
lead time is reduced from 33.6 hours to 28.6 hours, although the added value also decreases slightly. In the following section the impact that these values have on the PCE of the entire manufacturing process of the padel rackets is quantified.

In conclusion, the results shown in the new VSM (see, Figure 12) confirm that the improvements attained are significant: shorter lead time, possibility of redistributing resources (operators), lower downtimes due to higher machine uptimes (U/T) in the first cells, and scrap reduction in cutting, lay-up, and assembly.

The main purpose of the DMAIC methodology is not only improving process performance, but also having the improved results sustained in the long term. Therefore, standardising the optimal parameter settings is required. The critical curing parameters optimized at the assembly workstation are as follows: 50 minutes, 65 °C, and 3 bar. For measuring accurate values, a time controller, thermocouple sensors and pressure sensors are used. When applying these process values, the average scrap is 5%. As shown in Figure 13, control charts are plotted using Minitab software, and the poor adhesion defect is neutralized because the values are within the control limits. Therefore, the process on workstation 2 runs efficiently after the improvements as the scrap value is stabilized. The same procedure was successfully replicated for the control of CFRP material waste.

Finally, the following lessons learnt are highlighted within the framework developed: (a) whenever possible, test a new process, method, or material improvement apart from the daily production stage to minimize its influence in the rejection and production rate, (b) potential new enhancements coming into production for the first time require further attention, i.e., possible defects should be detected at a preliminary stage, (c) use control charts at each cell to keep the employees updated on the real time performance of the entire manufacturing process, (d) cross-functional teams are required to discuss any manufacturing problems and arrive at the solution

Figure 13. Control chart for scrap in assembly after implementing the strategy.



efficiently, (e) train operators in production and quality issues, as well as problem solving, and (f) periodically conduct one-point lessons to ensure operators follow the standard procedures.

### 5. Effectiveness of the proposed framework

As can be seen in Table 7, there is a significant improvement in the company’s key performance metrics achieved.

From Table 7 it is observed that raw material wastage in the manufacture of skins decreases to below 25%, which was one of the main goals of this research. Nevertheless, the rejection rate is still 2.3% above the target set for this cell and is divided into prepreg cutting (1%), lay-up (6%), and skin trimming (0.3%). On the other hand, the internal rejection rate has been reduced to 5% at the assembly workstation, and the external rejection rate is now only 0.3%. Therefore, two other major objectives of this case study have been fulfilled.

**Table 7. Comparison “before and after improvement” based on key metrics**

Key metrics	Before improvement	After improvement
Raw material waste C1	45.0%	24.0%
Internal rejection rate C1	18.3%	7.3%
Internal rejection rate C2	18.0%	5.0%
Internal rejection rate (average)	3.4%	1.2%
External rejection rate	8.0%	0.3%
Non-value-added time (NVA)	732.6 min	559.6 min (23.6%)
Non-value-added time but necessary (NVAN)	951.0 min	951.0 min (=)
Process Cycle Efficiency (PCE)	4.7%	5.5% (15.0%)
Material cost savings after improvement	18.5%	

In accordance with the reduction in lead time shown in the previous section, the non-value-added time has been reduced by 23.6% due to the reduction in reworking times (waste time) caused by the quality improvements. As a result, the process cycle efficiency for the entire manufacturing procedure has increased by around 15%. However, the PCE is not close to 10%, hence the overall production line is still far from achieving its optimal performance. The main cause is that the non-value-adding-but-necessary activities have been maintained (corresponding mainly to cells 4 to 6), and this represents a limitation of the current study. In addition, NVAN are typically reduced in the medium to long-term by changing equipment or processes (Henning & Moeller, 2011). Therefore, it is also recommended that in the near future efforts are dedicated to drastically reducing the drying times, either by changing materials, processes, or methods. Alternatives to increase the feasibility of manufacturing the product should also be explored, such as outsourcing cells 4 to 6 (priming, transferring, and varnishing, respectively), because these activities are not part of the manufacturer in question’s core business.

### 6. Conclusions

The conclusions of the present study are as follows:

- (1) A significant improvement has been detected in the key performance parameters after implementing the integrated model of the lean VSM tool supported by MFA into a DMAIC-based methodology (material waste, rejection rates, NVA time, PCE, etc.), as shown in Table 7. Most of the benefits expected from implementing this model in the composites industry have been accomplished. Therefore, the principles of lean manufacturing and Six Sigma have been effectively combined into one system for the in-depth evaluation and reduction of key parameters such as waste and rejection within the industry.
- (2) The significant factors that cause internal waste in the composite industry, particularly in the manufacture of padel rackets using composite materials, have been identified, quantified, and minimized. As a result, CoFRP waste reduction is 53%, leading to a more sustainable manufacturing process for composite padel rackets.
- (3) The root causes of the critical defects have been quantified and reduced by employing VSM support tools such as the Pareto chart or cause-and-effect diagrams. This has led to the almost total elimination of the external rejection rate (from 8% to 0.3%). Therefore, customer satisfaction has increased significantly.
- (4) A Lean Sigma strategy focusing the improvements on the most critical cells in manufacturing has resulted in a material cost savings of 18.5% per padel racket and a 15% increase in process performance.
- (5) The optimal performance of the overall production line was not reached because cells 4 to 6 have yet to be examined in depth, which is the limitation of the current work, and this could be the next objective of this study.

Implementing the tailored VSM-Six Sigma framework shown in this document, provided the company with a performance benchmark with which to implement future performance improvement programs. Moreover, the current framework openly discloses the guidelines followed so that experts in this field (academics, engineers, or operation managers) should be able to apply it easily and add their own improvements, thus bring the growing industry of composite materials closer to greater sustainability. That said, the proposed strategy needs to be validated in different scenarios to establish its full validity. This could also be considered another limitation of the proposed framework.

#### Author note

Mr. Jose Antonio González Ruiz is a PhD student at the Department of Mechanical Engineering & Industrial Construction, University of Girona, Spain. His main research focus is high-volume manufacturing of advanced composite parts. Within this framework, his current research is on implementing lean methodologies adapted to manufacturing composite material products. Furthermore, he is also working on curing kinetics and simulations of manufacturing processes for thermoset reinforced composite materials. Prior to this, he was a continuous improvement engineer for two years in the composite manufacturing industry.

#### Acknowledgements

This work was supported by the *Generalitat de Catalunya* through Grant number 2018DI0053.

#### Funding

This work was supported by the Agència de Gestió d'Ajuts Universitaris i de Recerca [2018DI0053].

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#### Disclosure statement

No potential conflict of interest was reported by the author(s).

#### Citation information

Cite this article as: Enhancing process performance for composite padel racket manufacture using Six Sigma-DMAIC and VSM synergetic support, Jose Antonio González Ruiz, Norbert Blanco & Marc Gascons, *Cogent Engineering* (2022), 9: 2084982.

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