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DESIGNING OUT WASTE FROM THE PRODUCTION OF A LEARNING TOWER THROUGH MATERIAL FLOW ANALYSIS

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Abstract: Malaysia's furniture manufacturing industry is made up of small and medium enterprises (SMEs), which contribute significantly to the country's economy. One major issue that these SMEs face is sustainable manufacturing: lowering throughputs and increasing production efficiencies. The study aims to improve the efficiency of producing a learning tower; a furniture product by an SME called Industerior Design by implementing material flow analysis (MFA) to monitor production throughputs. The MFA was used to compare two different learning tower designs (Design A and B). The most sustainable design was determined based on the MFA. A cause-and-effect analysis was also carried out using the Ishikawa fishbone diagram to identify potential causes of production inefficiencies. Both designs were proven to have the same processes involved and the same waste stream generated; however, Design A produces four learning towers from a single wood plank with 15.5% waste generated, while Design B produces only two towers with 44.6% waste generated. Of the waste generated by both designs, 60% from Design B was recyclable, while for Design A only 25% was reusable. Inefficiencies can be caused by a lack of skilled workers, a lack of or infrequent maintenance of equipment, or the design of the product itself. When the amount of recyclable waste that can be used for other future projects was considered, it was determined that Design B was more sustainable in the long run. MFA is thus thought to be a simple but powerful tool that can be easily implemented by SMEs in designing out waste from their products as the furniture industry moves toward more sustainable manufacturing and a more circular economy.

Keywords: circular economy; furniture industry; industrial metabolism; MFA; zero waste design

Introduction

The wood-based furniture industry is one of Malaysia's most important economic sectors, contributing more than 2 billion USD annually (Ratnasingam *et al.*, 2018). Malaysia is also one of the largest furniture exporters, ranking ninth among the world's leading furniture exporters (Ratnasingam *et al.*, 2018). The Malaysian government's initiatives to implement Industrial Master Plans beginning in the mid-1980s further aided the industry's advancement. Three master plans were developed, the most recent of which began in 2002. The most recent plan emphasises the use of more recent technologies, as well as competent design and product development. This includes adopting more environmentally friendly product manufacturing practices. Small and Medium Enterprises (SMEs) constitute the majority of Malaysia's furniture industry because of the industry's low entry barrier (Akbar *et al.*, 2017). This means that compared to other manufacturing enterprises, the capital required to enter this

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industry is relatively low. It also does not necessitate any high-level sophisticated technologies that other industries, such as pharmaceuticals, electronics, machinery, and others, require. Many SMEs in the wood-based furniture industry are having difficulty producing their products efficiently and sustainably (Aguilar *et al.*, 2017; Lee *et al.*, 2017). One of the causes of these issues is a failure to inventory the inputs and outputs of manufacturing activities. This issue is frequently caused by businesses failing to keep their records up to date consistently. Another factor limiting SMEs' ability to be efficient and sustainable in their product production is a lack of research and development (R&D). Most SMEs have limited R&D capabilities, coupled with limited funding and resources which makes it difficult for them to overcome this problem (Lee *et al.*, 2017; Yoshino, 2016). Inadequate waste management has also been a problem for SMEs (Yacob *et al*., 2019). Waste management is widely recognised as a critical component in achieving environmental sustainability.

Implementing Material Flow Analysis (MFA) during the manufacturing process can address this issue (Kluczek, 2019). MFA is a technique for quantifying how materials used in society are used, reused, and discarded (Graedel, 2019). MFA has been used as a tool for the development of waste management, sustainability and circular economy studies by a variety of parties ranging from industry players to researchers (Amicarelli *et al.*, 2021; Graedel, 2019). According to Roos Lindgreen *et al.* (2020), there is a need to link academician or research-oriented assessment methodologies such as MFA to business practitioners as the end user at the micro level in order to contribute to the global movement toward achieving a circular economy. Therefore, it is observed that studies on utilising MFA to promote SMEs to be more eco-efficient are still lacking, especially in Malaysia. This project aims to improve the efficiency of an SME, Industerior Design, in producing wood-based furniture products. The term efficiency in this project refers to the manufacturing of the selected product with little to no waste and the potential reuse or recycling of the waste produced for a better waste management strategy.

In this study, MFA was performed on a product called the learning tower. The learning tower is a piece of Montessori concept, wooden furniture designed for children that allows them to reach places that are higher than their height. The main reason this project has chosen the learning tower to focus on was that it is one of the best-selling products by Industerior Design. The company is continually receiving new orders for this furniture and is searching for ways to increase efficiency. Inefficiencies in building the towers include the issue of the amount of waste created and the techniques for dealing with the waste. A general practice by the company was to burn a majority of the discarded trash. The company will be able to determine the types of waste produced and which procedures produce the most waste by implementing MFA. The information gathered will help develop a more efficient manufacturing strategy, as well as determine proper waste management methods through greener design and the identification of waste-reduction opportunities. Hence, the objectives of this study were to evaluate two different learning tower design production processes using MFA, to identify the waste stream and waste quantity generated from the learning tower production processes, and to propose waste reduction and waste management strategies for increasing the efficiency of learning tower production based on the cause-and-effect analysis conducted.

Methodology

Steps in Material Flow Analysis

The MFA was carried out with modifications in accordance with the guidance provided by Brunner and Rechberger (2016). The project began by defining the spatial, temporal, and system boundaries of production. Second, data on the production procedures of the learning tower were collected. Third, qualitative and quantitative analyses were conducted. Finally, the results of the analysis were interpreted.

Spatial, temporal and system boundaries

To ensure that the study stays within its scope, spatial boundaries, temporal boundaries, and system boundaries have all been set. The location of the manufacturing process determines the spatial boundaries (Brunner and Rechberger, 2016). The workshop area owned by Industerior Design served as the study's spatial limit. A temporal boundary is a time constraint imposed on the amount of time required to construct a product (Brunner and Rechberger, 2016). The time required to build a full learning tower served as the study's temporal boundary. Depending on the company's productivity rate, the learning tower took between three and five working days to complete. The erection of a single learning tower served as the system boundary. The material compositions were restricted to the materials needed to build the furniture. Other elements, such as electricity and water consumption, were left out of the study. Other manufacturing processes, such as the manufacture of raw materials like wood boards and cosmetics, were also excluded. These factors will make the investigation move beyond its original focus.

Data collection

Based on the established boundaries, data on raw material inputs such as wood and outputs have been recorded. The construction processes for the learning tower have also been documented. The mass of wastes produced, such as sawdust and woodchips, was measured for the outputs. The kilogram (kg) was the standard unit of measurement used for the quantification of inputs and outputs. A commercial electronic scale with a precision level of 0.01 kg was used for this purpose. Because this project involved heavy objects weighing more than 20 kg, the use of this scale was justified.

All of the above information was compiled into an observation form. The observation form had three parts: the manufacturing process phase, the material inputs and outputs during each phase, and the mass of both inputs and outputs (Lombardi *et al*., 2021). There was only one type of input: raw material, which was the initial wood plank used. Product (the finished learning towers), stock, wood residues, and wood dust were among the output categories. Wood residues and wood dust were both regarded as waste outputs. There were two additional sub-categories of wood residues: recyclable and reusable wood residues and recyclable but non-reusable wood residues. Wood less than 2.54 cm in length was classified as recyclable but non-reusable waste. Woods with a length of more than 2.54 cm were classified as recyclable and reusable waste. This was because the company intends to keep these >2.54 cm wood residues for future projects.

Qualitative analyses

The manufacturing processes of the towers were monitored for qualitative analysis. The analysis tracks the material flows and quantities used in the tower's construction. Cutting, sanding, wrapping, and other processes were all documented. During each process, the type of output and its mass were also recorded. The analysis was presented using a flowchart (Brunner and Rechberger, 2016).

Quantitative analyses

For the quantitative analysis, data on the mass of input and output were gathered. The total mass of input and output must be the same. This is due to the law of conservation of mass, which states that no matter how an object's physical form changes, its mass remains constant (Sterner *et al.*, 2011). The data gathered also included the types of inputs and outputs produced, which were analysed using a balance table. A Sankey diagram will be used to visualise the balance table summarization. By visualising the material flow from beginning to end, Sankey diagrams are useful for identifying inefficiencies and potential savings in a production system (Lupton and Allwood, 2017).

Data interpretation

After the data analysis was completed, data interpretation began. At this stage, the main problem encountered during manufacturing, as well as the factors that contribute to it, were identified. The identified causes guided the recommendation of steps that could be taken to improve the manufacturing process. The cause-and-effect investigation took the form of a fishbone Ishikawa diagram (Dunuwila *et al*., 2018). The fishbone Ishikawa diagram is divided into two sections: the head and the bones. The main issue regarding the production of the learning tower was indicated at the head of the fish. The factors causing the problem, as well as their sub-causes, were placed along the fish's bones. There were three standard categories of factors that were used, namely the design, man, and machines.

Results and Discussion

Evaluation of two different learning tower designs through MFA

Figure 1 depicts two distinct designs for the learning tower created by Industerior Design. The basic design of a learning tower is Design A, which employs a rectangular and square-shaped concept with a three-level adjustable stepping platform. Design B incorporates a more stylish modern design for a learning tower that employs a trapezoid concept with a broader base with the same three levels of adjustable stepping platforms.

Figure 1: The learning towers which are Design A (left) and Design B (right) made by Industerior Design

Material Flow Analysis for Design A

It took about two days to complete the learning tower for Design A. The mass of inputs and outputs are detailed in the Sankey diagram (Figure 2). The company was able to create four learning towers from a single wooden plank. The wooden plank weighs 36.30 kg per product and was classified as the raw material input. The input resulted in four learning towers with a total weight of 30.65 kg. It was discovered that the production of four learning towers used approximately 84.55% of the raw wooden plank. It also produced 15.5% (5.65 kg) of the waste. Out of all waste generated, 56% (3.15 kg) is non-reusable but can be recycled, while only 25% (1.40 kg) can be reused and saved for future projects. Meanwhile, 19% (1.10 kg) of the waste generated was wood dust, which cannot be saved for any future projects.

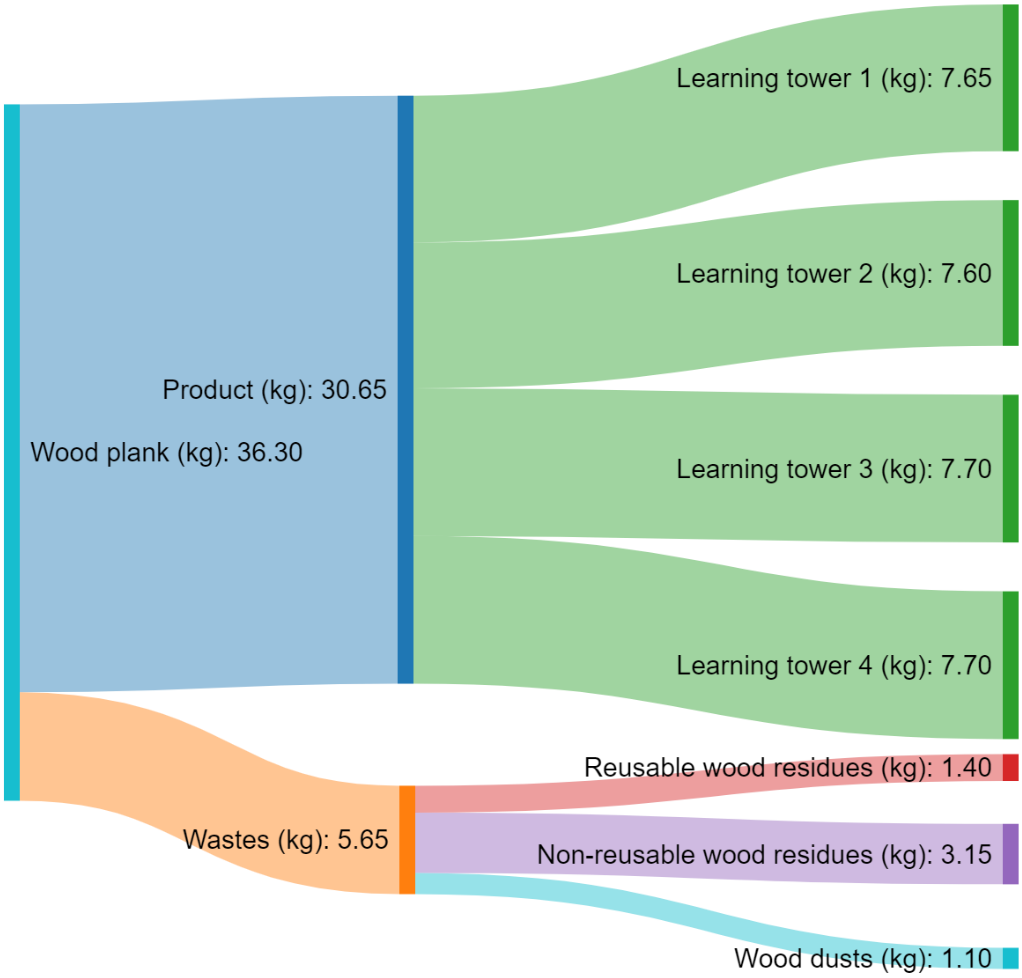

Figure 2: Sankey diagram of design A

There were 11 processes involved in the construction of this learning tower for this design. Figure 3 depicts the process in the form of a flowchart. The cutting process was discovered to be the major contributor to waste generation throughout the entire manufacturing process. During this process, a total of 4.55 kg of wood residues and 1.05 kg of wood dust were produced. Other processes, such as drilling, sanding, and trimming, produced wastes as well, but in small amounts that were undetectable by the scale. As a result, it was assumed that the waste generated was less than 0.01 kg.

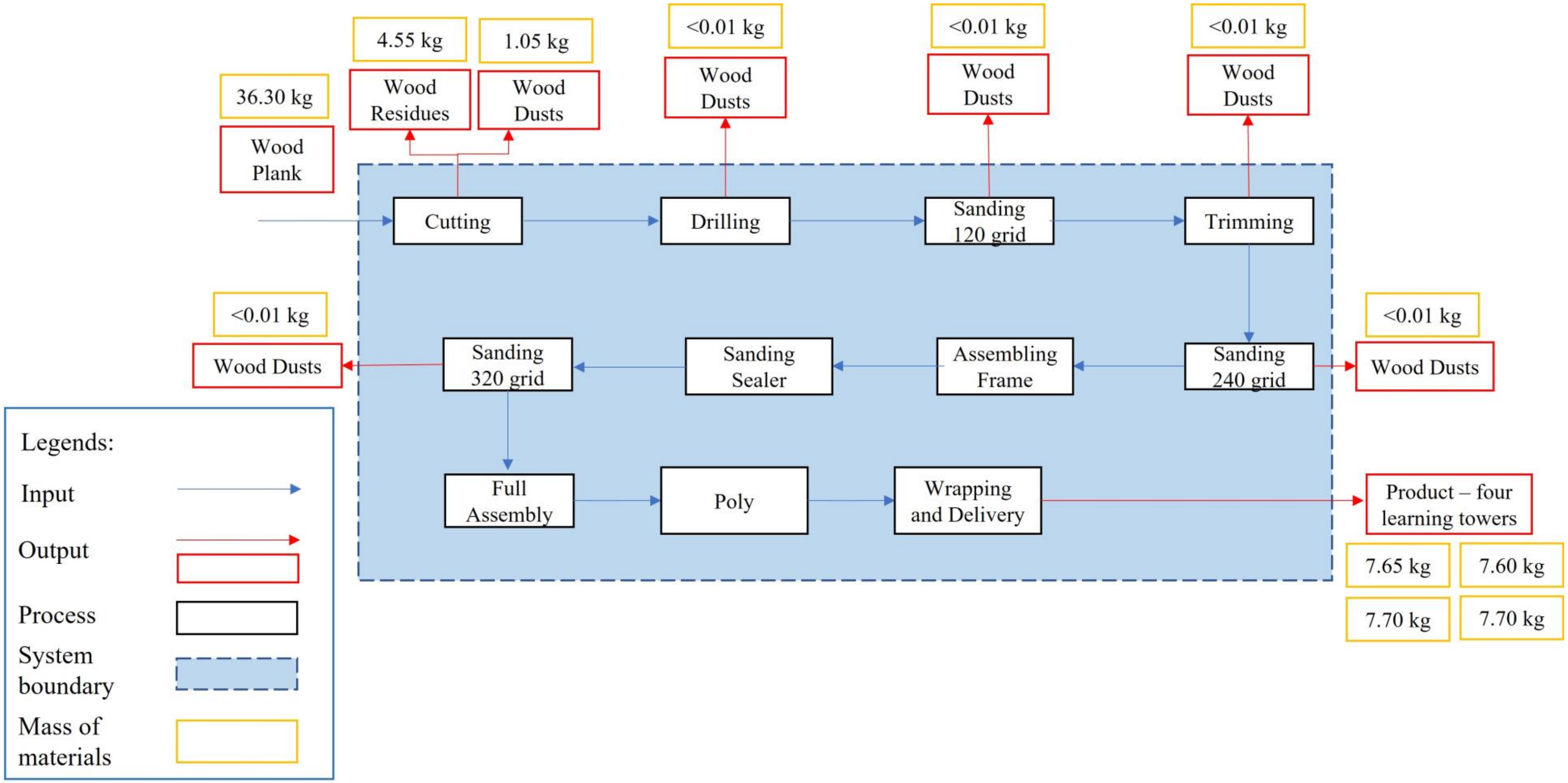

Figure 3: Flowchart for design A

Material Flow Analysis for Design B

This learning tower design takes approximately one and a half days to complete. They used the same size wood plank as in Design A, with a total input of 36.30 kg but only managed to produce two learning towers, each weighing 10.05 kg. This design used up approximately 55% of the raw materials in the manufacturing process. The waste generated was higher than in the previous design, which was 44.6% of the raw material. However, the amount of recyclable and reusable waste generated by Design B was greater than that of Design A. Sixty per cent of all waste produced was reusable and can be saved for future projects. Only 27% of the waste was non-reusable, with wood dust accounting for 13% of it. The Sankey diagram (Figure 4) depicts the result of the quantitative analysis done for this design.

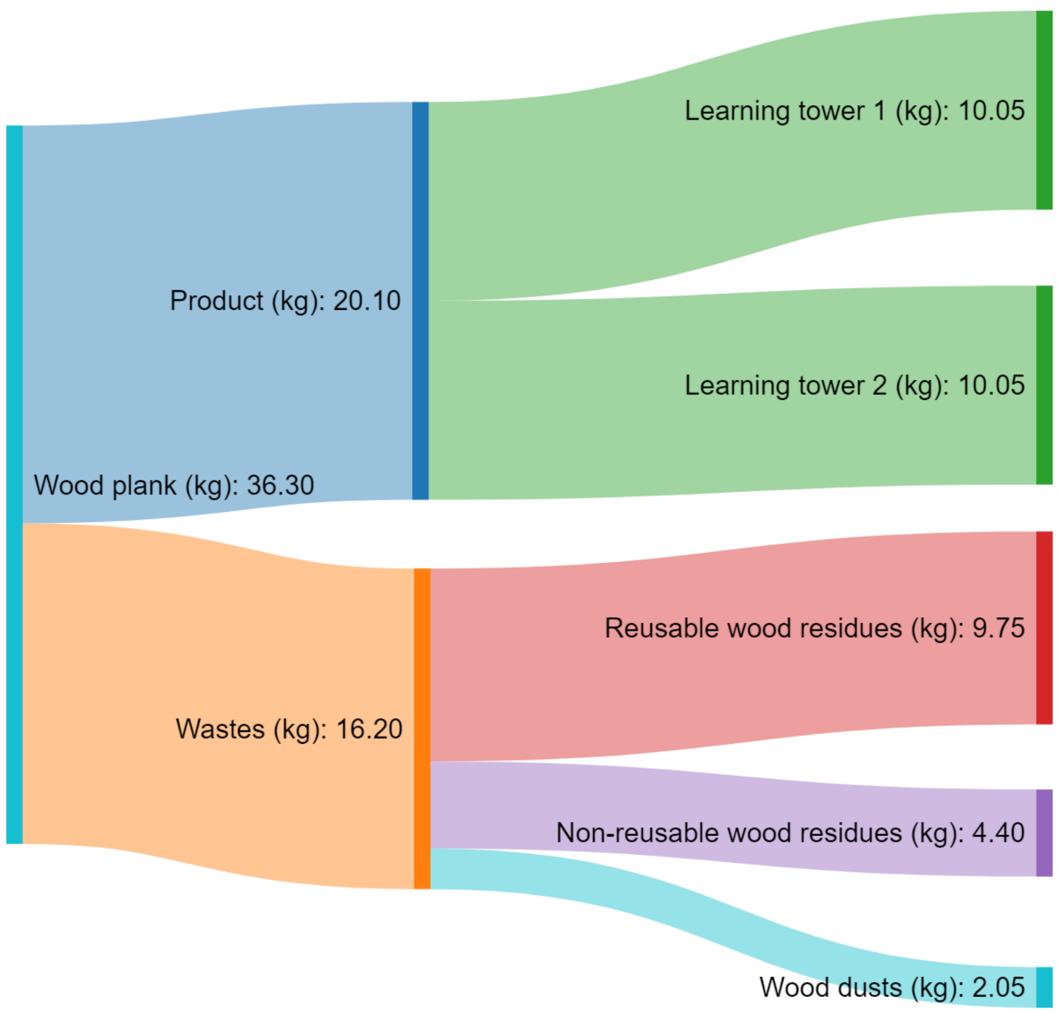

Figure 4: Sankey diagram for design B

This design has the same number of processes as the previous one but took a different approach in producing it. According to the flowchart for Design B (Figure 5), the cutting process was similarly the main contributor to waste generation, producing 14.15 kg of wood residues and 1.4 kg of wood dust. The trimming and slot making processes contributed 0.60 kg of wood dust, whereas other processes produce less than 0.01 kg of wood dust.

When the amount of recyclable waste that can be used for other future projects was considered, it was determined that Design B was more sustainable in the long run. This was also concluded based on customer demand based on the interview with the owner, with Design B having a higher demand than Design A. As a result, despite the fact that Design A produces more towers with less waste, it is determined to be less sustainable than Design B. With higher demand and more recyclable waste that can be used to make other types of wooden Montessori furniture or toys, Design B was selected as a more sustainable design, both in terms of the potential circularity of its production and its financial prospects.

Waste reduction and waste management strategies

To identify the causes that contribute to the company's problem, which was the amount of waste produced, a cause-effect analysis was performed. The cause-and-effect analysis was carried out using interviews with the company's owner and observations made throughout the manufacturing process. The fishbone Ishikawa diagram was used for the analysis (Figure 6).

The first factor identified was the labour involved in the construction of the tower. The only highly skilled employee was the company's owner. He usually hires part-time workers to assist him in finishing his products. All of the part-time workers he hired had no prior experience with woodworking, necessitating on-the-job training. This also restricts them to only using a few tools in the workshop, such as the sander, trimmer, and mitre saw. There were several instances where the part-timer made mistakes during production, resulting in waste. Their productivity has also suffered as a result of the error, which has increased the time required to complete a product. Another obstacle identified was the quality of the machines employed. The majority of the machines purchased were used second-hand machines. The lack of machine maintenance also contributes to waste production. A blunt saw can leave burnt marks on the surface of the wood (Kvietková *et al.,* 2015). Sanding is required to remove the burnt marks. More wood dust will be produced as a result of the process, increasing the amount of waste. The design of the learning tower was another factor identified that contributed to waste generation. Learning towers come in a variety of designs. The design chosen can have an impact on the amount of waste produced and the number of materials used. This was evident in this project, where different designs can have an impact on both parameters. Classic and modern designs based on market demands and trends may also influence this decision. Extra features or details required according to the desired design by customers may also result in waste production.

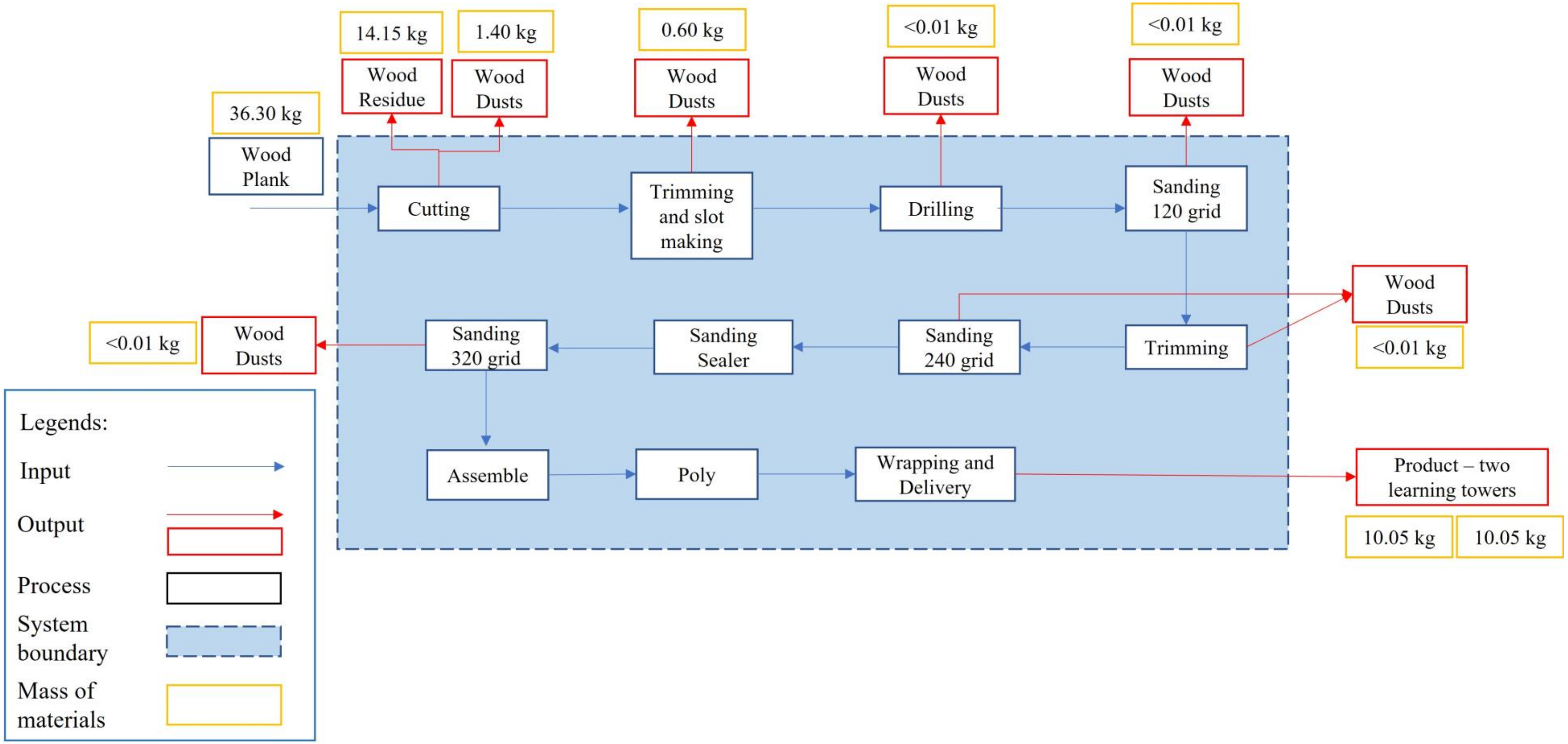

Figure 5: Flowchart for design B

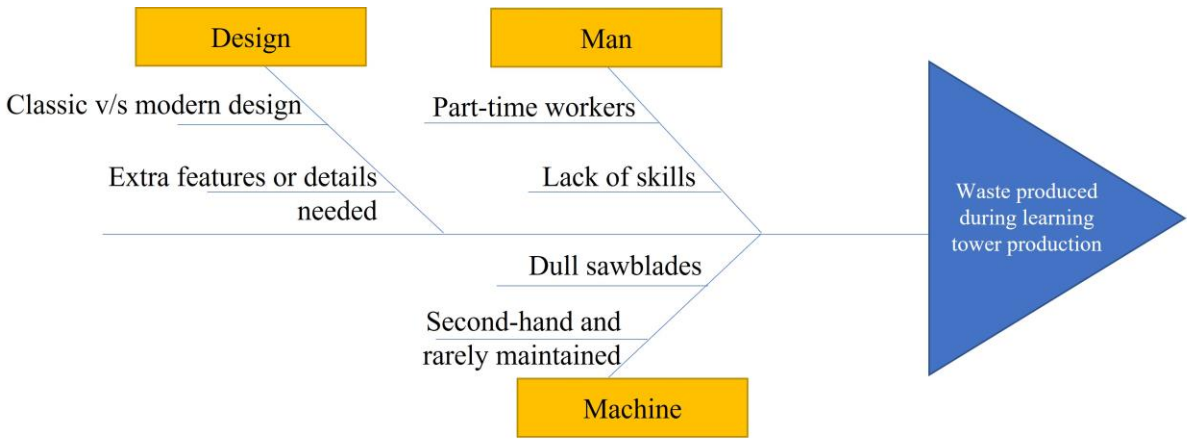

Figure 6: Ishikawa fishbone diagram for cause-effect analysis

To address the inefficiencies identified in the cause-and-effect analysis, several recommendations are made to reduce waste generation and manage waste generated in a sustainable manner.

In terms of design, one of the waste reduction efforts that the company can undertake is to use an eco-design approach in the design of the learning towers. The European Environment Agency defines eco-design as the incorporation of environmental considerations into the product design process while balancing ecological and economic requirements. The design considers environmental factors at all stages of the product development process, with the goal of producing goods that have the least amount of environmental impact possible throughout their life cycle. This includes, among other things, using renewable raw materials or fewer non-renewable resources, using wood resources that are planted and harvested sustainably (Armir *et al*., 2020), using non-hazardous materials for wood coverings and finishings (San *et al*., 2015), and reusing any waste generated along the product manufacturing and supply chain (Bianco *et al*., 2021). Others have demonstrated that eco-design has contributed to a 30% reduction in raw material use and a 49% reduction in waste generation (Aguilar *et al*., 2017). This method makes the best use of raw materials while minimising waste generated during manufacturing, lowering the overall environmental impact.

The efficiency of wood furniture manufacturing and the amount of waste produced can be affected by machine performance (Stasiak-Betlejewska *et al*., 2015). In order to address the issues raised in the machine category, the tools used in the construction of learning towers and other wooden products should be maintained and serviced on a regular basis. Investing in a newer, more efficient tool would be a better long-term quality improvement option.

Addressing the issues identified in the man category is similarly straightforward. Workers should receive intensive and ongoing training, especially if they are hired on a part-time basis. Hiring at least one permanent employee could be a good long-term investment, ensuring that the employee gains the necessary experience to work efficiently and assisting in the training of future employees. Developing guidelines, manuals, and standard operating procedures are another good practice that the company can use to ensure that knowledge and skills are transferred to workers in a sustainable manner.

Finally, in order to address the main problem at the top of the fishbone Ishikawa diagram, waste generation and sustainable waste management with a closed-loop strategy are proposed. The concept of circularity in wood waste management has been investigated, and evidence suggests that the possibility of reusing wood waste is extensive throughout the life cycle of a wood-based industry (de Carvalho Araújo *et al*., 2019). The generated wood waste can be reused by the company or by selling them to other businesses that can use them. As a manufacturer of wood-based products, Industerior Design can develop new innovative wood-based product ideas that utilise the waste produced. The wood wastes generated can also be sold to composting companies, where the wood chips (short, unusable wood wastes) can be used as bulking agents in composting processes (Liu *et al*., 2020). Others may also use the wood dust produced as animal beddings (Owoyemi *et al*., 2016), or it can be pressed and upcycled into low-cost wood planks. Wood dust can also be used as a fuel source to heat structures and homes (Top, 2015), or it can be combined with other waste to generate energy (Akhator *et al*., 2017). The woods are converted into biomass, which is then used to generate electricity, heat, and transportation fuel. Hence, wood residue management can be profitable for the company by collaborating with others that can process them into high-value products.

Conclusion

The project's overall goal was to use MFA to improve the learning tower production process. Following the evaluation, both designs produced a different number of products while generating the same amount of waste. Design B was found to be more efficient and sustainable than design A. This is because the amount of recyclable and reusable waste generated by design B was higher than that of design A. Several factors contributed to the manufacturing processes' inefficiencies, including a shortage of skilled workers, poor tool maintenance, and poor product design. The MFA tool was found to be simple enough for SMEs to use while also being powerful enough to help with waste-free product design. This would help furniture manufacturers transition to more sustainable manufacturing and a more circular economy.

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Declaration of Interest Statement

The authors declare that they have no conflicts of interests.

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