A Case Study of University–Industry Collaboration for Sustainable Furniture Design

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Abstract: This paper describes the importance of including a Human-Centred Design (HCD) approach for successful university–industry collaboration. We detail user surveys and user evaluation techniques to engage end-users for the rejuvenation of manufacturing industries through sustainable product development. There are numerous studies describing the importance of university–industry collaboration; however, very few portray the detailed working relationships necessary to fulfil both the university and the industry agenda. This paper explores a joint project between a prominent Melbourne-based university and a government organisation from Malaysia. The intention was to innovate a range of furniture for Malaysian dormitories to stimulate the local manufacturing sector and provide high-value product applications for Malaysia’s abundant timber sector. By detailing a HCD approach, we reveal how to better direct the design outcomes to accurately reflect the research intent. This is detailed through a case study showing how the research data was translated into final product concepts influenced by end-users and collaboration with the industry stakeholders. The resulting products are a range of sustainable, modular dormitory furniture with a direct route to market. Finally, we provide the lessons learned and suggestions for developing sustainable products through university–industry collaboration.

Keywords: university–industry collaboration; new product development; user-centred design; sustainability; Human-Centred Design (HCD); industrial design; innovation; user experience

1. Introduction

Many manufacturing companies are looking to innovate and evaluate existing products to understand their current value and identify market gaps and opportunities [1]. Often, internal assessment is done within the manufacturing company to brainstorm new product opportunities that match organisational capabilities. However, the issue is that many of these manufacturing companies—while skilled manufacturers—are not trained in design; hence, new product development can be challenging [2,3]. Therefore, organisations often look for external sources for collaboration [4], such as with universities, where engagement activity has recently increased [5].

A Human-Centred Design (HCD) approach has become an accessible method for many of these industries who are looking to innovate their product range but perhaps do not know where to start, and therefore, it is suggested to enhance industry–university collaboration through design research [6]. A HCD approach has been adopted as a business strategy to enhance commercial success where understanding the needs of customers is paramount [7]. Common global products such as furniture can benefit greatly from user perspectives; however, manufacturing industries may not fully understand how to implement a HCD approach to advance product innovation within their organisation.

Artefacts (artificial objects) come into being through intent [8]. Design implies a conscious, purposeful activity to arrive at a state which did not previously exist in order to (presumably) improve some (perceived) unsatisfactory existing state of affairs [9]. This was...
a key focus of the Malaysia Automotive Robotics and IoT Institute (MARii) that supports Malaysia’s manufacturing industry to innovate their current manufacturing capabilities and stay sustainable. They serve to advance the development of strategic and operational intelligent systems through the humanisation and utilisation of smart platforms and expert design. A joint venture between Swinburne University of Technology in Melbourne, Australia, and the Malaysia Automotive Robotics and IoT Institute (MARii) was formed to develop a range of modular dormitory furniture manufactured by local industry in Malaysia to stimulate growth in their abundant timber sector. Dormitory furniture was chosen because it was seen as a direct route to market and a popular product category requiring innovation. User research was a critical component of this project, and it was important to gain insight into the user needs early in the project to ensure the outcome of sustainably successful products. The intent set out by MARii for this study was to stimulate growth in the State of Sabah, Malaysia, which has an abundance of sustainable plantation timber with limited high-value application. This led to a partnership between MARii and the Centre for Design Innovation at Swinburne University of Technology to use industrial design as an enabler to innovate local manufacturing for the purpose of creating sustainable products using local resources. To do this effectively, we used a HCD approach to ensure the developed products matched user needs and preferences, as understanding user intentions and how they interact with given products is a core part of a HCD approach [10].

The importance of considering sustainability in product development has grown over the years because of the environmental and economic benefits it brings to new product development. There is increasing consumer interest in environmental responsibilities in the furniture industry [11]. The inclusion of sustainability in every stage of the design process is highly beneficial to manufacturing industries, especially during the early stages of design to ensure the concepts developed meet sustainability objectives. The sustainable approach from the initial phase developed a wider scope for both environmental and social sustainability [12]. Product innovation with such sustainability consideration helps educate manufacturing partners who perhaps want to become more sustainable but do not know how to. It is essential to provide the industry partners with an opportunity to realise the value and market potential of a newly developed product [13], making it the design team’s responsibility to understand sustainable principles and processes and ensure the concepts presented to the partners include these. Integrating both users and industry partners in this process will generate successful design opportunities [14], which is evidenced in the case study presented in this paper.

2. Innovation for Sustainable Product Design

Sustainability perspectives have been touched different domains such as higher education [15] and product innovation to achieve sustainable development goals (SDG). Sustainability has a link to product innovation [16,17] due to the importance of the topic. There have been many successful practices of design-driven innovation and methods for implementing sustainability in product innovation [18]. Companies are looking to innovate sustainable products; however, not all companies understand how to apply the sustainability principles [19] and the benefits of HCD in their cycle of product development. In most cases, the user usually gets involved after the product development as a consumer rather than an integral part of the development. The cost of not recognising the value of a HCD approach is high, especially in developing countries [20].

Through a case study presented in this paper, a HCD approach is described to show how it directly influenced the product direction leading to a range of sustainable modular dormitory furniture manufactured by local industry in Malaysia. The researchers and designers involved in this study demonstrate how a HCD approach was successfully implemented and balanced with the user information data with their own design knowledge. In this paper, sustainable product development not only represents the material but also the
sustainable life cycle of new product production. This is where innovative opportunities are key to unlocking a new source of competitive advantage [21].

In the past, the term ‘human factors’ in an engineering and manufacturing context illustrates human ergonomics and physical functionality [22,23]. While understanding ergonomics for this study was vitally important, the need for understanding user perspectives became key to ensuring sustainably successful outcomes could be achieved. For the design team based in Melbourne to develop appropriate products that would ultimately be manufactured and used in Malaysia, an in-depth understanding of user needs was required. This approach stems from the late 1990s, where a technology-driven focus shifted to human-centred interaction. With this shift, HCD provided tools for innovation, supporting the company’s manufacturing agendas [24]. HCD creates new product opportunities by involving the end-users who can draw expertise from their perspective rather than purely the design team’s knowledge. As discussed by Lyon et al. [24], HCD relies heavily on qualitative inquiry to understand contextual constraints and user needs, as well as the evaluation of products that may require multiple iterations.

A HCD approach often unveils certain aspects of product innovation which was hidden under ‘status quo’ manufacturing systems and the extent of knowledge of the design team. Many manufacturing industries in developing countries are in this dilemma. Understanding culturally appropriate innovations through user perspectives is vital for these industries and was extremely important for this study. According to Lyon et al. [24], HCD is currently underemphasised and underutilised during the implementation stages for successful sustainable products. The application of a HCD approach in product development needs to be encouraged throughout the design process and not just at the front-end, and the design team must be able to design sustainable products based on the social impact of the product life cycle [25]. By including a HCD approach, companies can create a valuable relationship with the users [21]. This user interaction is of utmost importance when designing with a ‘user-pull’ approach.

The main purpose of a HCD approach is to develop a product that matches the users’ needs and preferences [26]. Steen [26] argues that understanding the balance of users’ knowledge and designers’ knowledge when using a HCD approach is crucial for innovative solutions. A HCD approach plays an immense part in developing not just another alternative solution but an innovative solution for the company. This approach was used in both the intervention and implementation stage of the design process of this case study. While the focus was on the user, the evaluation of manufacturing capabilities, an audit of material availability, and feasibility in design and production were also evaluated in the design process.

Aims and Scope

We followed a design process with a HCD approach that grounded the product development with data collected from users before any physical design activity started. This particular method is similar to a ‘market-pull’ approach, where user analysis of needs and wants is the key focus of the product development [20]. As we are designing a furniture range for users who are not the purchasers, we deem our study as a ‘user-pull’ approach. ‘Pulling’ ideas from the end-user perspective in the early stages of the product development process helped create targeted innovation for the local manufacturing industry. Therefore, the key aims of this project were to investigate how sustainability can be embedded in the HCD approach, particularly in designing new products, and how successful university–industry collaboration can occur by developing user-centred sustainable products.

A majority of the industry-linked projects conducted within the Centre for Design Innovation are focused on helping diversify output for manufacturing companies with the goal of producing more sustainable products. Our study shows how engagement with universities can help assist through the development of sustainably successful products that fit within the existing capabilities of these manufacturing companies. The companies that engage with universities for these activities are highly skilled manufacturers and often have
expert engineers, but a vast majority have no expertise in developing sustainably successful products and taking them to market. That is not their skill set, as they have never had to do this before. This is where collaboration with universities is useful, as the missing skills can be acquired, and the core business of the manufacturing company is not jeopardised. In this paper, by detailing a HCD approach, we reveal how to better direct the design outcomes to accurately reflect the research intent. This is detailed through the following case study showing how the research data translated into final product concepts influenced by end-users and collaboration with the industry stakeholders. The key contribution of this paper is to demonstrate how sustainability considerations can be embedded in the design process to develop products for successful university–industry collaboration.

3. Case Study: Sustainable and Modular Dormitory Furniture

This research project is a partnership between Swinburne University in Australia and the Malaysia Automotive, Robotics, and IoT Institute (MARii). The project involved designing, developing, and manufacturing furniture, including a bed, closet, bookshelf, storage cabinet, desk, and shoe rack. Acacia timber was chosen, which is abundant in sustainable plantations in Malaysia, and when final pieces are manufactured, the furniture will be installed in MARii campus dormitories. If deemed successful, the furniture will then be considered for other markets both domestically and internationally.

This project stems from an associated gap in the timber manufacturing industry and furniture market identified by MARii and Swinburne University during initial project discussions. Swinburne University as the lead partner made connections with local manufacturers and suppliers and collaborated with them to produce the new furniture range for compact dormitory living. The project not only aimed to educate and grow the manufacturing industry but also provide a sustainably successful solution to the level of compact living associated with a dormitory environment. The final design consisted of a basic bed that modularly interlinks with or adapts to become various other furniture components. In terms of research aims, the main aim of the user research was to improve the experience of students living in a dormitory. User surveys and relevant HCD methods were used to assess the primary needs and preferences of students, and this information informed design decisions when developing a new range of smart, compact furniture for dormitory rooms. This furniture provides a better living and studying environment for future students at MARii campuses, and the insights gathered have the potential to contribute to other research projects of a similar nature. The case study presented as follows shows how users’ and stakeholders’ perspectives were utilised to shape the final design of smart dormitory furniture that consists of bedding with modularity to interlink with and adapt to various other furniture components.

3.1. Method

The design process, which included four phases (see Figure 1), was used in this case study to structure the university–industry collaboration. The case study focused on user perspectives, with its core aim being revitalising the Malaysian timber furniture industry by introducing new innovative products.

![Diagram of the design process](Figure 1. Four design phases diagram.)
3.2. Phase 1: Exploring the Design Opportunities, Sustainable Materials, and Principles

In the initial phases of the project, a gap in dormitory furniture purposefully designed with user input was identified. It was found that the current furniture was not designed for purpose and required replacement regularly, as the quality was poor, and it lacked any form of innovation. The furniture was also imported from neighbouring South-East Asian countries, outlining lost opportunities for the local manufacturers. To create an innovative solution, a HCD approach was introduced as a form of product intervention, and modularity was a key design feature for both ease of manufacturing, individual customisation, and ease of end-of-life disassembly.

We also explored existing products, established a range of aesthetic directions for the intended furniture, and identified the core materials such as *Acacia mangium*. There are many species of Acacia, but *Acacia mangium* is the most common plantation species in Malaysia. Native to Australia, Papua New Guinea, and Indonesia, this species is a popular choice for forest plantation due to its robustness, adaptability, and fast growth. *Acacia mangium* remains the preferred plantation species in Sabah and Sarawak. The use of sustainable plantation timber from the Sabah region of Malaysia was also key to stimulating the local manufacturing sector. The timber species is said to be underutilised, mainly due to insufficient details on the physical and mechanical strength properties of the timber. The species was originally planted for pulp and paper production, but its use has expanded to other industries, including furniture-making. It is currently used for plywood manufacturing and sawn timber production both for non-structural and structural applications.

As this project was aimed at providing smart furniture solutions reflecting users’ needs and preferences, the modular design considerations helped enable this. An in-depth understanding of users’ needs is critical to product innovation [27]. With minimal user involvement in the past for the furniture used in the Malaysian dormitories, we developed a user survey distributed to dormitory residents to ensure early stages of the design process were founded on user knowledge that would help shape the direction of the project. The following section describes the four phases in detail to clarify our approach.

Survey with Dormitory Users

We received 34 completed surveys specifically targeted at dormitory residents in Malaysia. Surveys with unanswered questions were removed from the sample size, and the conduction of surveys was approved by Swinburne University of Technology Human Research Ethics Committee (Ref: 20203047-4744). Previous survey studies focused specifically on design report meaningful findings using similar (or smaller) sample sizes to that of this study. Ankrah and Langford [28] used 22 responses in their analysis of an organisational culture in architecture. Osmani et al. [29] attained 40 usable respondents to collect data on architects’ perspectives on reducing construction waste. Because of the niche focus in this study (dormitory users’ perspective), 34 respondents is deemed adequate as a means for constructing design guidelines in the early stages of the design process.

The user survey questions in our study were developed based on current dormitory observations that formed an extensive body of work prior to this study. The survey consisted of 20 questions focusing on ‘likes’ and ‘dislikes’ about their dormitory experience. We focus the results on the major findings from the survey that were genuinely used to shape the direction of the dormitory furniture. We concentrate on ‘likes’ and ‘dislikes’ (see Figure 2), as well as the external influences of how a resident uses their dormitory space. The survey data was analysed using the SPSS software. Relevant descriptive statistics were calculated for each of the survey questions.
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The survey data was analysed using the SPSS software. Relevant descriptive statistics were calculated for each of the survey questions. Figure 2.

**Figure 2. User survey: General likes and dislikes about dormitory rooms.**

For 'likes', feeling comfortable and spacious was highlighted as key functions of a positive dormitory space. On the other hand, 'dislikes' spanned a wider variety of themes, some of which can be directly impacted by the newly developed furniture, such as lack of privacy and security; damaged equipment, indicating longevity/quality required in the newly developed furniture; and ambient temperature, as Malaysia is a hot, sub-tropical country.

How the users interact with their dormitory space was also analysed (See Figure 3). While most people prefer to study in various shared locations on campus, a portion of respondents (18%) prefer to study in their dormitory rooms. This validates the need for a desk, but it would likely not be utilised by every resident.

**Figure 3. User survey: Use of the dormitory space.**

A number of shared desks located throughout the room would offer those who want to study in the dormitory a comfortable, functional place to do so. Unsurprisingly, most of the time people spend in their dormitory room is spent sleeping. Studying/working
makes up a small portion of time; however, this could be attributed to the fact that there are no desks currently provided. A key takeaway from this user survey is the amount of time people spend socialising and relaxing in the dormitory: 32% when combined. This emphasises a need for flexibility created through modularity in the bunk bed designs that allow users to relax privately some of the time and use the space in a more open, shared manner when socialising with friends at other times.

3.3. Phase 2: Concept Generation and Evaluation

During Phase 2, initially, the design team conducted several rounds of ideation and generated several concepts that focused on (1) ease of manufacture and simplicity, (2) flexibility and versatility, (3) customisation and personality, and (4) comfort and privacy (see Figure 4).

Design for Disassembly, Maintenance, and Repairs

The design team considered sustainability principles [30–33] at the beginning of the project. For instance, during the ideation phase, the design team considered several principles for sustainable furniture design. Design for disassembly is a design philosophy that allows products to be broken down into different parts at their end of life, which aids in reusing and recycling. This principle was explored for the furniture pieces to reuse the timber components or recycle them into another product or service—e.g., paper pulp. Fixtures, finishes, and construction methods require consideration to achieve a final design that can be disassembled and reused. As these furniture pieces will be used on a daily basis and by various inhabitants of the dormitories, it is assumed that repairs will be necessary at some point in the products’ life. Consideration was given to design furniture that would be durable enough to withstand its intended life and be repairable in the event of a breakage. The design team reviewed eight joining methods for the initial concepts. The joining methods were butt (with cam lock nuts), butt (with screws), mitre (with screws), dowel, mortise and tenon, dovetail, metal brackets, and interlocking pieces. During the early ideation phase, the design team utilised the joining methods and evaluated them against existing furniture on the market. For instance, one of the concepts focuses on flat-packability and storage integration. Such furniture could be made up of panels that utilise industry-standard connection methods or even interlocking features.

Based on the analysis of results from the user survey, the initial concepts were revised, and four design concepts were developed (see Figure 5).
Concept 1: This concept has a boxy shape that lends itself more towards basic construction methods that have been commonplace among bedroom furniture for decades.

Concept 2: This concept features a single bed design that can be stacked on itself to create a bunk bed. Connections for this concept could be borrowed from a design like the ‘Scoopbunk’.

Concept 3: This concept focuses on flat-packability and storage integration. It could be made up of panels that utilise industry-standard connection methods or even interlocking features.

Concept 4: This concept sits at the higher end in terms of comfort, features, and overall design. It creates a private space for each occupant of the bunk, adding stylised storage to the end.

All concepts maximised the use of the timber resource *Acacia mangium*, a plantation timber grown in abundance in the Sabah region of Malaysia, where this project was positioned. The concepts also considered manufacturing capabilities from this region, and, importantly, all concepts embodied the major findings of the user survey and were used as a key tool for design evaluation.

Each of the four concepts captured certain characteristics identified from the survey. They were generated from the industrial design team associated with the project using 3D CAD software and computer renderings. The research team mapped the survey findings into four categories as follows:

1. Manufacture: Ease of manufacturing based on local manufacturers’ existing capabilities.
2. Modularity: Interchangeable design, flat-pack construction, and customisation. Individual units can be easily replaced/repaired without affecting the whole system.
3. Flexibility: Ability to change configurations and individualise the furniture.
4. Comfort: Adequate ventilation, privacy, socialisation, and secure storage.

These categories were evaluated against each concept to provide greater clarity around the incorporation of research findings into the virtual concept renderings (see Figure 6).

![Figure 5. Four design concepts.](image)

3.4. Phase 3: Iteration and Validation

All four concepts were presented to the industry members (n = 14) of MARii and the internal design team members (CDI) (n = 10) for a post-survey evaluation. A weighted
feedback method was used to categorise the evaluation comments to narrow them down to one final concept (see Figure 7). Weighting attributes based on a scoring system are usually used to sort and prioritise data analysis of surveys, feedback, and discussions [34].

Figure 7. Weighted feedback chart (Score 1 lowest–4 highest).

The weighted feedback revealed Concept 4 as the most preferred design. After analysing the captured feedback, affinity clustering was used to group comments (see Table 1) into common themes. A particular theme can include positive, negative, and opportunity comments. Where themes feature mostly positive comments, designers and researchers can understand the elements of each concept that worked well and select features or aspects of the concept to incorporate into the refined design.

Table 1. Summary of the findings from the feedback session.

| Concept | Positive Aspects | Negative Aspects | Opportunities |
|---------|------------------|------------------|---------------|
| Concept 1 | Storage was a big positive. Providing ample space, flexibility, and convenience The simplicity of the design was well received; however, improvements were suggested (such as rounding over sharp corners) The simple and modern aesthetic | Concerns regarding the perforated panels and how easy they would be to clean Concerns around the safety of the ladder design Concerns around the lack of flexibility | Create a roof for the top bunk for additional safety and privacy Integrate a power source Make the beds easy to assemble/disassemble Refine the design to include more rounded edges Integrate features from the other concepts, such as the rotating towel rack and pegboard |
| Concept 2 | The design aesthetic was a positive feature Perceived modern design Airy/open A practical and flexible design The design has a small footprint Personalised space | The design lacks features such as a drying rack, additional storage, power outputs, and shelving Durability concerns regarding the fabric components Safety concerns regarding the ladder | Refining the design to include power outputs, additional storage, drying rack, and desk drawers Make the design more durable |
Many of the findings from the user survey confirm design decisions that have been made to date, such as the need for more privacy, secure storage, and a place to study. Some results were surprising and have led to invaluable insights that influenced the direction of the design during refinement, such as a strong emphasis on the social connection within the dormitory rooms. After analysing all the valid responses to the Dormitory Satisfaction Survey, the key findings were converted into a list of user needs (see Table 2) that guided the final design direction.

Table 2. Refined user needs for developing the selected concept.

| User Needs | Desired Features | Other Key Insights |
|------------|------------------|-------------------|
| – Greater privacy | – Mirror | – Shared desks are sufficient when space is tight, as not all students like to study in the dormitory |
| – Greater security for their belongings | – Towel rack | – Students spend a significant amount of time relaxing and socialising in the dorm room. |
| – Space to relax (private) | – Drawers, lockable storage | – Creating a feeling of ‘personal space’ is subjective; having the option to personalise the space could improve satisfaction. |
| – Space to socialise (open, flexible) | | – Many students value the room feeling spacious and dislike it feeling crowded. |
| – Options to personalise their space | | – Space for relaxing and sleeping needs the most improvement. |
| – Comfortable environment (cool, quiet, clean) | | – Students suggest that changing the layout of the room, increasing privacy, and improving cleanliness could create their ‘ideal’ dorm. |
| – Keeping the bunks compact to achieve a sense of space | | |
| – Quality, reliable, durable furniture (does not break or is easy to maintain and repair) | | |

During Phase 3 (Iteration and Validation), the design team developed literature on *Acacia mangium*, which was the preferred timber selected for this project. Because of the fast-growing nature of this timber, along with its dimensional stability, attractive exterior aesthetic, and sustainable resourcing practices, the concepts maximised the use of this material, which ultimately generated more productivity to the sector. *Acacia mangium* is also native to Australia, making it ideal for the design team to access this material to test and prototype throughout the project.

3.5. Phase 4: Refinement, Prototype, and Deliver

After a thorough analysis of the feedback received from the project stakeholders, the results of the user survey, and the design team concept review, Concept 4 was selected to move forward with Phase 4 of the project. The overall aesthetics and features of the design were refined and improved based on the feedback received from the survey. The feedback on all four concepts was taken into account and considered in the refinement of
the final direction. Features that received positive feedback from Concepts 1, 2, and 3 were be incorporated into the refined direction where possible. For example, we considered bedside shelving and modular storage from Concept 1; ‘airiness’, curves, and options for personalisation from Concept 2; and finally, flexible storage, movable dividers, and compact towel rack from Concept 3. Aspects of the concept that received negative feedback were removed or refined, with all the suggested changes considered.

Concept 4, with its high-end aesthetic, flexible configurations, compact footprint, sense of privacy, and ‘pod-like’ feel, was most appealing to move forward as a final design. Minor revisions to the design focused on incorporating additional storage within the bed frame (shelves), as well as exploring options such as under-bed storage, modularity within the wardrobe, and a more intuitive and functional towel rack. Powered accessories such as lights, fans, and charging points were further explored and integrated into the design. There was also consideration to ‘opening up’ the bed frame to allow for greater airflow, light, and for ease of changing mattresses and sheets while maintaining the option to create a closed-off, private space when desired. Personalisation of the space was a key consideration, as well as the ability to utilise the beds in a wide range of configurations to suit the needs of different users and future markets. Ease of manufacturing and assembly was refined with the intent to reduce weight, enable easy transportation, and decrease material costs. Figure 8 shows the refined design.

![Figure 8](image-url)

**Figure 8.** The final design aesthetic: a single bed that can be stacked to form a bunk.

**Finite Element Analysis (FEA)**

Before concluding Phase 4, SolidWorks 2021 Finite Element Analysis (FEA) (Static) simulation software was used for testing the strength of the single bed and bunk components to provide validation of the designs before moving to expensive testing and production. Four different tests (see Table 3) were simulated to assess the strength of the single bed and bunk to provide validation of the designs before we moved to the prototyping stage. The preferred concept (Concept 4) passed all simulated strength tests and moved to prototype development for ergonomic evaluation and final product refinement.
Table 3. Summary of the tests for checking the strength of the single bed and bunk components.

| Test Type                          | Force Allocation/Materials                                                                 | Results/Comments                              |
|-----------------------------------|------------------------------------------------------------------------------------------|-----------------------------------------------|
| Specifications: The product must be able to withstand 200 kg evenly distributed across the bed surface. A Factor of Safety (FOS) of 2 has been used for the simulations. | Material Properties for *Acacia mangium* for simulation properties are listed below. Poisson’s Ratio: 0.33 Shear strength parallel to the grain: 12 MPa Density: 530 kg/m³ Tensile strength: 140 MPa Compressive strength: 34 MPa Yield strength: 72 MPa | NA                                             |
| Test 1: Single bed                | Force 1: 400 kg (FOS × 2) = 4000 N Force location 4000 N total across each contacting face. Force 2: Uprights and Top section (including fasteners) = 25 kg (250 N) Force location of 250 N on receiving cavity of legs. | Stress results: Pass Stress Max = 7.728 MPa, Yield of Material = 72 MPa Displacement results: Pass Max Displacement = 0.0212 mm max |
| Test 2: Bunk bed assembly          | Force 1: Top Bunk Assembly Weight = 46.6 kg (466 N) Top Bunk Load = 400 kg (4000 N) Top Frame Bottom Bunk = 25 kg (250 N) Total Force 1 = 4716 N Force Assignment = Across all 4 legs of bottom bunk bed Force 2: 400 kg (FOS × 2) = 4000 N Force Assignment: Force location 4000 N total across each contacting face. | Stress results: Pass Stress Max = 7.61 MPa, Yield of Material = 72 MPa Displacement Results: PASS Max Displacement = 0.0213 mm max |
| Test 3: Bunk bed assembly legs evaluation | Force allocation: Top Bunk Assembly Weight = 46.6 kg (466 N) Top Bunk Load = 400 kg (4000 N) Bottom Bunk Assembly Weight = 46.6 kg (466 N) Bottom Bunk Load = 400 kg (4000 N) Total Force 1 = 8932 N Force Assignment = Across all four legs of bottom bunk bed | Stress results: Pass Stress Max = 6.8 MPa, Yield of Material = 72 MPa Displacement Results: PASS Max Displacement = 0.06144 mm |
| Test 4: Bunk bed assembly uprights evaluation | Force 1: Top Bunk Assembly Weight = 46.6 kg (466 N) Top Bunk Load = 400 kg (4000 N) Top Frame Bottom Bunk = 25 kg (250 N) Total Force 1 = 4716 N Force Assignment = Across all 4 uprights | Stress results: PASS Stress Max = 0.4 MPa, Yield of Material = 72 MPa Displacement results: PASS Max Displacement = 0.0294 mm max |

During Phase 4, the prototyping of Concept 4 was done to evaluate ergonomics and usability. Prototyping in a 1:1 scale was critical by provided realistic measurements that could be cross-referenced against key findings from the user survey. Overall dimensions, including the bed height, the length privacy panels extended out, and division and size of storage were all altered based on this evaluation. Initial installation of the bed slats and mattress all worked well, with the mattress and slats being retained by the side walls. The overall length and width of the bed were driven by the mattress size. Additional height at the head and the foot of the bed were included to accommodate taller users and ensure a user’s head did not hit the top support while sitting on the edge of the bed. This was important, as one of the key findings from the user survey was the ability to socialise within a dormitory, which would usually take place while sitting on the bed rather than laying on the bed. The ergonomic assessment also resulted in minor adjustments to the overall height of the bed to not only ensure a user’s head did not obstruct the top support but also to allow a larger shelf/drawer at the bottom of the bed for storing valuables, as well as comfortably fitting shoes, which was not possible before this refinement (see Figure 9).
Phase 4 concluded when these proposed changes were successfully delivered to MARii, along with a complete FEA and full manufacturing flow analysis. All refinement was now complete, and final designs were prepared for final production.

4. Discussion

By connecting universities with industry, research will be more relevant, and the knowledge will help us understand how to develop a sustainably successful product. Kuys et al. [2] argue that research-led practice in design research provides a platform for establishing the application of design theories in practice. Design practice is directed by research, where concepts generated through design practice provide evidence that research-led design practice can generate a new body of knowledge. This study demonstrates this by providing a range of new sustainable products influenced directly by research that benefits both users and manufacturers. Through the case study, we establish how this is done by highlighting successful methods of engagement, as well as the difficulties that can be encountered between working across academia and industry.

4.1. Considering Sustainability in the Design Process: Implications for HCD

Integrating sustainability into the design process was crucial for our project. We followed a HCD approach; however, the approach itself was not sufficient for developing sustainable furniture. Researchers have utilised a variety of models to integrate sustainability into the design of products [35,36]. Hence, from the beginning of the project, the design team considered sustainability in all phases of the design process from initial sketching through to detailed engineering drawings ready for production. Furthermore, we considered sustainability in material selection, product finish, transportation, assembly and disassembly, maintenance, and repair of the designed furniture. Moreover, in developing the furniture, the design team considered three key aspects of sustainability: environmental sustainability, economic sustainability, and social sustainability [37]. Adhering to those three aspects were necessary during the HCD approach, and the amalgamation of both approaches (i.e., HCD and sustainability) assisted in developing the desired product that was deemed successful by the industry partner. Insights from our project suggest that, for developing user-centred sustainable products, key aspects of sustainability need to be considered throughout the HCD process. In our project, the synergy between sustainability and HCD provided the key benefits for developing sustainable products. Therefore, we believe that, to some extent, our approach is similar to the hybrid model called ‘User-Centred Design for Sustainability’ (UCSD) [38]. Though the UCSD tool could be used to assess the degree of sustainability of a product, it is necessary to investigate how it could be utilised to develop products with commercial goals and multiple stakeholders.
4.2. Developing Sustainable Products Using a HCD Approach to Foster University–Industry Collaboration

This case study addressed how a HCD approach can add value to manufacturing industries by creating product innovation that aligns directly with user needs. The HCD approach used in this study demonstrates the importance of embracing the user perspective throughout the design process to influence the design concepts from an early stage. This study amplifies the innovative opportunities derived from a HCD approach in anticipation of many other manufacturing industries struggling to develop a competitive market solution. From a practical point of view, the outcome of this project provides a much-needed rationale behind using a HCD approach for other manufacturing industries to follow.

The innovation was driven by the continual user involvement throughout the design process since the involvement of the customers helped to reveal the key needs of the end-users and related stakeholders [39]. It is also noted that, while the design is subjective and products developed will not always please the user, this study shows an approach to mitigate ‘dislikes’ by involving end-users in the formation of design guidelines. This method helps capture user perspectives for a design team to implement for greater acceptance and success of the final design outcomes. During the project, it was easier for us to convince the stakeholders because the HCD approach helped to gather evidence from the end-users. Eventually, the stakeholders did not oppose to the design decision and accepted the potential concept for further development. At the time of writing, final product manufacturing has commenced.

4.2.1. Prototypes for Effective Communication with the Stakeholders and the Role of the HCD Process

In this project, we developed several low- and high-fidelity prototypes and evaluated them against the research findings. We visualised the sketch and physical prototypes to obtain early feedback from the stakeholders. Our design team developed and refined prototypes iteratively and validated them with stakeholders and end-users throughout the project. In line with existing studies [40], in our project, prototyping was crucial in the success of developing sustainable commercial furniture. The HCD process also had an influence on the prototypes that were built during the process. As a design team, we did the design exploration before receiving the end-users’ and stakeholders’ feedback. That feedback contributed to refining the initial direction of the project and, finally, to designing endorsed, sustainable furniture. Consequently, the development of the prototypes helped to build trust with the stakeholders and assisted in creating a safer communication channel [41] for collecting richer feedback. Therefore, the HCD process, particularly the co-creation activities (feedback sessions on the sketches, prioritising user and stakeholder needs, and assessing the physical prototypes), contributed to developing shared understanding and building a sustained trusted relationship with the stakeholders. In line with existing studies [42,43], the tangible prototypes also acted as a catalyst to develop a shared understanding of the envisioned product between the university research team and stakeholders from the industry.

4.2.2. Engagement with Stakeholders, End-Users, and Design Team Members

Constant collaboration with the industry partner throughout the entire process was vital for our project. Stakeholders were actively involved in the ideation and concept development phase that proved to be useful for developing the product. We used the company’s skills to improve design outcomes and ensured they fit within the company’s capabilities. This makes the company feel significantly involved in the products and gives a sense of ownership. This assists products to move from a conceptual stage to commercialisation, as they want to see ‘their’ own ideas come to fruition. Frequent updates to the client throughout the project ensured that stakeholders understood the design process and minimised the concern during the project execution. The paying company
appreciated our ongoing contact and fortnightly updates, especially when the findings of each of the four phases were shared.

The design research team that played a vital role in the project was multi-disciplinary, from identifying the market gap to delivering the final product. Fundamental research and market identification were required to ensure a market gap to develop the most innovative product. The university design research team had the necessary skills to develop the intended product, as well as investigate the competing products that were deemed inadequate. The university project team consisted of design researchers, industrial designers (for concept generation, CAD, user-centred design, material selection), product design engineers (for refinement/manufacturing details), and marketing/business personnel and one project manager (for timelines, the main point of contact for client, accountability, quality control, innovation–new ideas). The researchers and designers involved in this study demonstrate how a HCD approach was successfully implemented and balanced with the user information with their own design knowledge. Likewise, the stakeholders from the industry focused on how to make the envisioned product commercially successful. Therefore, the shared goals between university researchers and industry stakeholders were shaped by a collaborative process. Industry stakeholders and design team members developed shared understanding [44] while materialising the end-users’ feedback.

4.3. Sustainability in Product Development: Design for Disassembly, Reuse, and Recyclability

Embedding sustainability in product development and manufacturing creates a healthy, productive environment for social sustainability [12]. Selecting appropriate materials for product development plays a critical role that affects the sustainability performance of the product and its design process [45]. This is not just about selecting ‘sustainable’ materials but materials appropriate for the design context with an inherent sustainable value and are long-lasting, durable, and fit for purpose. Environmental, social, and economic impacts were present from the beginning of the product design process to ensure the design team maximised sustainable attributes for the final outcome. These additional sustainable considerations increase supply chain resilience and value for the customer. As suggested by Shaharussaman et al. (2021), we used a screening method constructed on a knowledge-based system to compare different materials for use in the early phases of concept development. *Acacia mangium* was chosen as the primary material because it is locally produced, decreasing transportation emissions and costs. Stainless steel and brass fixings were chosen to complement the aesthetics of *Acacia mangium* and are much better quality than less superior metals. While slightly more expensive, the long-term sustainability benefits are paramount in creating a product that boasts longevity, which in turn reduces the replacement cycles that many poorly designed and manufactured furniture pieces require. During the design process, design for disassembly was incorporated to allow the product to be easily disassembled to separate materials for end-of-life reuse and recycling. Design for disassembly can create a product that enables a high percentage of reuse and recycle [46]. The final product was refined to minimise material usage, ease disassembling, and incorporate quality fixings that would not break down over time. Furthermore, it is expected that the aesthetic value of the final furniture will lead to maintaining them for years, and consequently, the considerations for aesthetic sustainability was achieved through our design [47]. The approach used for this followed emotionally durable design (EDD) principles originally conceived by Chapman [48]. This was because the principles of longevity are apparent in both the physical and emotional drivers of the final outcomes. EDD approach aligned perfectly with our HCD methodology. It is a user-focused approach to product longevity that examines and articulates the unspoken emotional experiences that occur between products and consumers, seeking to uncover the complex emotional drivers for why we use, consume, and discard some products faster than others [48]. This view inspires a reduction in consumption and waste of natural resources by encouraging more durable, resilient relationships with products, highlighting that product longevity needs to be concerned with not only the physical lifetime but also the psychological lifetime of the
product [13]. We demonstrated this within our survey, which mapped findings against four core categories: Manufacture and Modularity (physical constraints) and Flexibility and Comfort (emotional constraints). By doing so, we have created a furniture solution that is not only physically better than what exists (durable materials, stronger fixings, stable design, etc.), but it is also psychologically better (improved ergonomics, better comfort, increased privacy, etc.).

Modularity in construction is a known design feature that has an impact on sustainability [49]. In our design, modularity was an essential feature because the furniture components need to be flat-packed for shipping. It is the combination of physical design interventions such as modularity allowing for ease of disassembly for end-of-life, increased quality of materials and manufacturing, and a more intuitive design that meets the needs of users that makes for a more sustainable design outcome. From a material perspective, end-of-life principles were considered by minimising materials that have a detrimental effect on the environment when discarded. Sustainable plantation hardwood dominates the overall product with minimal use of metals for structural and practical components (hinges, hooks, and fixings). As we are using a quality hardwood species that boasts durable characteristics, as opposed to an inferior softwood species, the timber can be repurposed easily. While discarding the material at end-of-life is the least desirable option, the timber will naturally decompose, unlike competitor materials used in furniture such as plastics. Adhesives are not used at all, relying purely on fixing hardware to secure the furniture, which is critical for disassembly at end-of-life, as well as logistics when flat-packing the designs for transportation.

5. Conclusions

This paper presents a case study of a partnership between industry and university to innovate sustainable products using local resources. We used a HCD approach to ensure the developed products matched user needs and preferences. The design process, which included four design phases, was used in a case study to structure the university–industry collaboration. The case study focused on user perspectives to revitalise the Malaysian timber furniture industry by introducing new innovative products. This study demonstrates how engagement with universities can help develop sustainably successful products that fit within the existing capabilities of manufacturing companies.

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