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The Development of an Automated Multi-Spit Lamb Rotisserie Machine for Improved Productivity

Xun Wei Chia [1], Poh Kiat Ng [1,*], Robert Jeyakumar Nathan [2], Jian Ai Yeow [2], Way Soong Lim [1] and Yu Jin Ng [3]

1 Faculty of Engineering and Technology, Multimedia University, Jalan Ayer Keroh Lama, Bukit Beruang, Melaka 75450, Malaysia; chiaxunwei@gmail.com (X.W.C.); wslim@mmu.edu.my (W.S.L.)
2 Faculty of Business, Multimedia University, Jalan Ayer Keroh Lama, Bukit Beruang, Melaka 75450, Malaysia; robert.jeyakumar@mmu.edu.my (R.J.N.); jayeow@mmu.edu.my (J.A.Y.)
3 Department of Social Science and Humanities, Putrajaya Campus, College of Energy Economics and Social Sciences, Universiti Tenaga Nasional (UNITEN), Jalan IKRAM-UNITEN, Kajang 43000, Malaysia; yujin@uniten.edu.my
* Correspondence: pkng@mmu.edu.my

Abstract: Innovations in food manufacturing support the agenda for sustainable development goal 9 (SDG9) on industry, innovation and infrastructure. Pursuant to this goal, this study aims to develop an automated multi-spit lamb rotisserie machine that potentially improves the lamb-roasting productivity for small and medium enterprises (SMEs). The conceptualisation involved patents, scholarly literature and product reviews of lamb-roasting devices. The design and analysis are performed using Autodesk Inventor 2019. A scaled-down prototype is developed and tested with (1) roasting output, (2) roasting time and (3) temperature stability tests. The data for test (1) are analysed by comparing the means between control and experimental groups. The data for tests (2) and (3) are analysed using the *t*-test and Mann–Whitney U test, respectively. Significant differences are observed in tests (1) and (2), with outcomes being in favour of the proposed invention. The prototype cooks 92.27% faster with 700% more meat than a regular lamb roaster. It also cooks at a stable temperature. The cost analysis indicated that this invention could be sold at USD 278 if mass-produced. The design is structurally simple, inexpensive and easy to manufacture, allowing SMEs that rely on traditional spit-based machines to enhance their ability in producing roast lamb.

Keywords: rotisserie machine; engineering design; productivity; roast lamb; meat; usability; SDG9

Citation: Chia, X.W.; Ng, P.K.; Nathan, R.J.; Yeow, J.A.; Lim, W.S.; Ng, Y.J. The Development of an Automated Multi-Spit Lamb Rotisserie Machine for Improved Productivity. *Machines* **2021**, *9*, 165. https://doi.org/10.3390/machines9080165

Academic Editors: Raffaele Di Gregorio and Benoit Eynard

Received: 5 July 2021
Accepted: 9 August 2021
Published: 11 August 2021

1. Introduction

Innovation- and productivity-driven small and medium enterprises (SMEs) play an important role in propelling the advancement of middle-income countries to high-income nations [1–3]. In Malaysia, SMEs are the drivers of the economy, accounting for 38.9% of the country's GDP in 2019, which is an increase of 0.6% from 2018 [3,4]. For food sector SMEs, there is a need to develop smart, energy-saving and cost-saving technologies in supporting the United Nation's objective for SDG 9 (industry, infrastructure and innovation) [5–7]. One of the growing food SMEs in Malaysia includes the lamb-roasting industry.

Roast lamb, or also known as Kambing Golek in Malay, is a dish where a whole lamb is roasted on a rotisserie machine. This dish has a deep cultural significance in Malaysia and Indonesia, especially during the Eid al-Adha festival where roast lamb is often prepared for the celebration [8].

Malaysia, in particular, often sees a steep increase in the demand for roast lamb around the middle of the year. In a survey, it was found that sheep or goat meat is consumed by 72% of Malaysian consumer respondents. This meat delicacy is normally served at celebration banquets, restaurants and hotels [9].

Seasonal changes in the demand introduced several problems for roast lamb suppliers. One of the problems includes the difficulty in increasing roast lamb productivity. The roasting process for a single lamb takes about 4–5 h, and while being roasted, the lamb needs to be basted once every 15 min to prevent the loss of moisture in the meat [10]. During seasons of high demand, the quantity of roast lambs that a vendor can produce is limited by the number of roasting machines they own. Moreover, a traditional lamb-roasting machine is only capable of roasting one lamb at a time and takes up an area of approximately 900 mm $\times$ 400 mm [11].

The contemporary solution that vendors often consider to fulfil the high demands on roast lambs is to purchase more roasting machines. The average cost for a single-spit lamb rotisserie machine ranges from USD 150 to 350. Hence, this solution might not be ideal as the investment-to-profit ratio is rather low, and the supplier may face problems storing the unused machine during seasons of low demand.

Problem Statement

There have been a few products developed in the market that attempted to solve the productivity issues in meat roasting. In the rotisserie chicken industry, a machine known as the 1425.4SMiE uses four spits with independent motors to increase the capacity of chicken roasting. In the 1425.4SMiE, a total of 20 to 24 chickens can be roasted to completion within 1.5 h [12].

Some existing products use infrared as the heat source to replace conventional heating methods such as charcoal and gas. This type of roasting method has its benefits, such as short preheating duration and evenly distributed heat [13]. Compared to charcoal roasting, which has a preheating duration of 15 min, an infrared burner takes only 3 min to preheat. This duration excludes the time taken to arrange the charcoal on the tray and to start the fire [14].

Nonetheless, the above-mentioned features are not applicable for the mass production of roast lambs for several reasons. The cooking method for a roast lamb is already well established, and having charcoal as the heat source is an important factor due to customer preferences for charcoal roasting over other roasting methods. The long cooking duration allows the charcoal to infuse a smoky aroma into the meat that other types of heat sources are unable to render. This aroma stems from a chemical compound known as guaiacol [15]. Guaiacol is an aroma compound produced when heat is used to break down lignin, the resin responsible for holding strands of cellulose together to form wood [16]. Food produced from charcoal grills often has this smoky aroma that most people associate with roast lamb.

In the case of machines such as the 1425.4SMiE, it is not applicable for mass production in the context of roasting lambs due to the high cost required. A whole lamb weighs about 18 to 22 kg, while a whole chicken weighs around 2.2 to 3.2 kg. Hence, the motor power output required to rotate one whole lamb on a spit would be higher compared to the output required for a few whole chickens on a spit.

The aforementioned limitations in existing solutions assert that there are no studies that investigate inventive solutions applicable to roasting lambs for improved productivity. Hence, the study aims to develop an inventive solution that is capable of solving the inherent productivity issues of existing lamb-roasting machines in the market.

This study adds value to the community of researchers in the area of machine design as it accounts for underlying stages in the mechanical design process, which includes conceptualisation, design, development and usability evaluation [17]. There is also a need for machine designers to advance from developing rigid, single-output and manual machines to flexible, multi-output and automated machines to stay formidably competitive in productivity, efficiency and operating cost [18,19]. As such, with a special emphasis on lamb roasting, this study serves as a beneficial reference for machine design researchers in their quest to improve the productivity of their machines inventively and at a reduced operating cost.

2. Literature Review

The lamb-roasting machine is classified as a rotisserie machine because of the nature of its cooking method. Rotisserie, also known as spit roasting, is a roasting method where the meat is skewered on a spit. A spit refers to a slender solid rod used to lock the food in place while it is being cooked on fire [20]. This cooking method is common for roasting whole animals because it not only cooks the meat evenly in its own juices but also facilitates continuous basting [21]. The rotisserie cooking method is found to be used as early as the Tudor Period (1485–1603). In those days, the spit was operated through manual rotation, usually by a servant of a large community. Later on, mechanical "roasting jacks" or turnspits were invented to cook more efficiently. These devices were first powered by dogs on treadmills and by steam power and clockwork mechanisms later on [22]. Other mechanisms, such as worm gears (for torque and speed transmissions), were also used in the past.

Currently, electric motors are often the preferred actuators for lamb rotisserie machines due to the high reliability of the motors. A conventional lamb-roasting machine is characterised by a few features, namely the electric motor for automatic rotation, stainless steel body, charcoal as the heat source and grilling platforms for auxiliary cooking. There are advantages and disadvantages to each of these features.

Electric motors assist in rotating the spit. As opposed to manual rotations, rotating with electric motors eliminates the need for manpower to rotate the spit, which is considered a one-dimensional task for a worker. Although electric motors are reliable solutions, the motors are not fully utilised in conventional lamb rotisserie machines. For instance, while a 15 W electrical motor used by a lamb rotisserie product may be able to provide a torque of about 6800 Nm, the amount of torque it takes to turn a 70 kg lamb is only about 800 Nm. This condition indicates that only around 12% of the motor's turning power is utilised to turn a single lamb.

2.1. Contemporary Lamb-Roasting Devices

2.1.1. Existing Product Review

Product 1: Electric Grill Stainless Spit Roaster [23]. The body and frame of this modern lamb rotisserie machine are made of stainless steel. Stainless steel is a common choice for such machines because it prevents surface corrosion, which is important when cooking is involved. The maintenance of stainless steel products is also easy. If utilised properly, products made from stainless steel can be expected to last for many years [24]. This product is designed to make use of charcoal as the heating source. It is also equipped with four lockable wheels for easy manoeuvring. Table 1, which was adapted from [23], shows a summary of its features and specifications.

Table 1. Summary of the features and specifications.

Price	USD 268.59
Features	Height adjustable, automatic rotation, lockable wheels, peripheral accessories
Grill Type	Charcoal grill
Material	Stainless steel
Dimension	400 mm (W) × 1180 mm (L) × 800 mm (H)
Motor specification	28 W, 110 V/50 Hz

Product 2: XL Lamb Rotisserie [25]. This lamb rotisserie device is manufactured by an Austrian company known as the Pig Lamb Rotisserie Shop and is sold on their website at the price of 279 USD/unit. Similar to Product 1, this rotisserie machine uses an electric motor to turn the spit. It includes a 110 V 40 W and 2.5 RPM motor capable of turning

an entire lamb that weighs 57 kg at most. The spit is 1650 mm in length and 33 mm in diameter.

In contrast to the previous device, which has four legs with lockable wheels, this device only has two legs supported by three beams in a tripod formation. This design also does not possess a stainless steel body to hold the charcoal. Instead, the user is expected to set up an area for the charcoal in between the device's legs.

Although this design lacks manoeuvrability and built-in charcoal storage features, the 2-legged design is more segmented and can be taken apart when it is not in use. This aspect makes it portable. Table 2, which was adapted from [25], shows a summary of the device's features and specifications.

Table 2. Summary of the features and specifications.

Price	USD 279
Features	Automatic rotation, high portability, ease of assembly
Grill Type	Depending on user
Material	Stainless steel spit, stainless steel hooks, cast iron stands
Dimension	Height: 250–500 mm; Spit: 1650 mm, 32 mm diameter
Motor specification	220 V, 3 RPM—up to 50 kg

2.1.2. Patent Review

Charcoal Barbeque Rotisserie Grill Cooker [26]: This invention is a charcoal-fired barbeque grill that transforms interchangeably between two cooking modes, namely rotisserie cooking and barbeque grill. It comes in a compact and portable design and has a charcoal basket, which rotates between a lowered horizontal orientation for grilling and a raised vertical orientation for rotisserie cooking. A handle located outside the cooker's frame is used to change the cooking modes.

The rotisserie spit lowers into the container along the sidewalls of the cooker's frame. When the charcoal basket is upright, a drip pan can be placed under the spit. In order to ensure that hot air flows over the roast, a combination of vents and a heat shield located between the vertical charcoal basket and the back wall of the cooker is included. The handle on the lid can be used to pick up the entire cooker.

Charcoal Grill [27]: This invention provides a method of igniting charcoal with improved safety and convenience compared to the traditional methods of charcoal ignition. This design requires only 1 to 2 sheets of newspaper to ignite any number of charcoal briquettes piled above the hole in the bottom of the bowl. Bringing the charcoal to a condition that is ready for cooking requires about 5 to 10 min depending on the amount of charcoal ignited.

This invention uses a few sheets of newspaper to start the fire, which is safer than methods that require the use of flammable fluid. Another advantage of this invention includes the prolonged life of the grill, which is applicable if the user complies with the recommended guidelines of use. These guidelines include using the grill without any layers of gravel, aluminium foil or the like. After the cooking is done, the coals should be burned out, and the ashes should be raked towards the hole at the grill's base. The ashes go into the receptacle for further disposal. Alternatively, water can be sprinkled on the coals to douse the embers. The excess water will flow out of the hole at the grill's base together with the dirt and ashes.

2.2. Cooking Method (Roasting/Rotisserie)

Roasting is a way of cooking that uses dry heat where hot air is used to cover the food, cooking it evenly on all sides [28]. The style of roasting known as rotisserie is commonly used because of the enhanced flavours that stem from the caramelisation and Maillard browning on the surface of the food. Maillard browning happens when the water molecules on the surface of the food are eliminated, and molecular rearrangement occurs, which subsequently produces the Amadori product (1-amino-1-deoxy-2-ketose).

The Amadori product does not contribute to flavour but is an important precursor for the flavour compound [29].

Compared to the faster types of roasting, such as oven roasting, rotisserie cooks the meat at a much slower rate, which allows the meat to retain more of its original moisture, dissolves more of the collagen that makes the meat tough and improves the meat's tenderness.

The tenderness of roast meat is greatly affected by the temperature and time of roasting. This relationship has been studied empirically. In a particular study, around 240 roasts were cooked to calculate the ideal cooking time [30]. Table 3, which was adapted from [30], shows the recommended cooking times for the corresponding lamb roasts.

Table 3. Cooking time (min/kg) for roast lamb in varying doneness degree.

Type of Roast	Doneness Degree	Recommended Time of Cooking (Min/kg)
Leg, whole bone-in (3.2–4.1 kg)	Rare Medium Well done	33–44 44–55 55–66
Leg, boneless (2.3–3.2 kg)	Rare Medium Well done	55–66 66–77 77–88
Leg, shank-half (0.9–1.8 kg)	Rare Medium Well done	66–77 88–99 99–110
Leg, sirloin-half (1.1–2.3 kg)	Rare Medium Well done	55–66 77–88 99–110
Shoulder, boneless (1.8–2.7 kg)	Rare Medium Well done	66–77 77–88 88–99
Shoulder, pre-sliced (0.9–2.3 kg)	Rare Medium Well done	77–88 88–99 99–110
Seven-rib rack (0.7–1.1 kg)	Rare Medium Well done	66–77 77–88 88–99
Crown-rib, not stuffed (0.9–1.4 kg)	Rare Medium Well done	33–44 55–66 66–77

The findings suggested that the lamb roasts increased in doneness with time. There was no difference observed between the rare and medium groups of pre-sliced shoulders. This outcome was the same for the medium and well-done groups of the boneless leg, seven-rib rack and crown-rib roasts. An average increase of 15.6 min/kg was required to raise the internal temperature from 60 to 70 °C, while an average of 11.4 min/kg was needed to raise the internal temperature from 70 to 77 °C. In terms of reaching a common internal temperature, the time/kg value required was found to be lesser in larger roasts than in smaller roasts [30].

2.3. Meat Doneness

Doneness is a measure of how thoroughly cooked the piece of meat is based on its internal temperature and colour when cooked. The definition and gradation in relation to its internal temperature vary across different dishes. For steaks, common gradations include rare, medium rare, medium, medium well and well done [31]. Apart from investing in proper cooking equipment, it is important to monitor meat doneness when roasting to avoid food safety concerns and prevent serious foodborne illnesses such as food poisoning, typhoid, cholera, hepatitis A and dysentery [32–34].

The United States Department of Agriculture (USDA) recommends that for cuts of beef, veal and lamb to be considered safe for consumption, the internal cooking temperature should be at least 145 °F (63 °C) [35]. The same meats should be thoroughly cooked to 160 °F (71 °C) when ground or tenderised by cutting since these processes distribute bacteria throughout the meat. Table 4, which was adapted from [35–37], shows a scale used for meat doneness concerning beef and lamb.

Table 4. The meat doneness scale.

Description	Scale	Temperature Range		USDA Recommendation
		°C	°F	
Very red	Extra rare	46–49	115–125	-
Red centre; soft	Rare	52–55	125–130	-
Warm red centre; firm	Medium rare	55–60	130–140	-
Pink and firm	Medium	60–65	140–150	145 °F and rest for at least 3 min
Small amount of pink in the centre	Medium well	65–69	150–155	-
Gray-brown throughout; firm	Well done	69–71	155–160	160 °F for ground beef
Blackened throughout; hard	Overcooked	>71	>160	-

3. Materials and Method

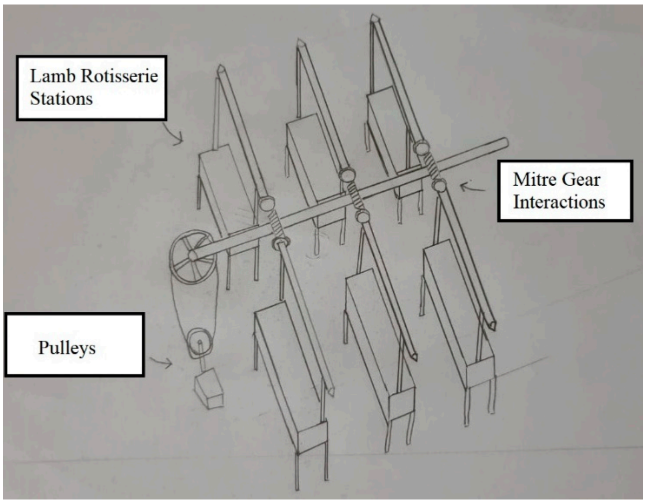
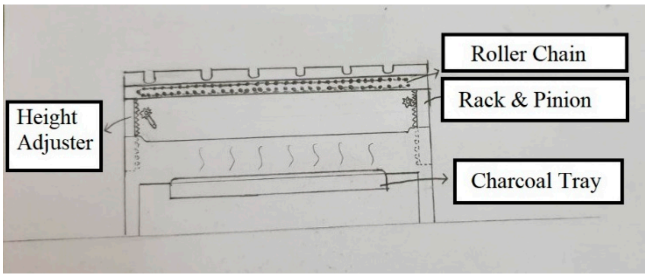
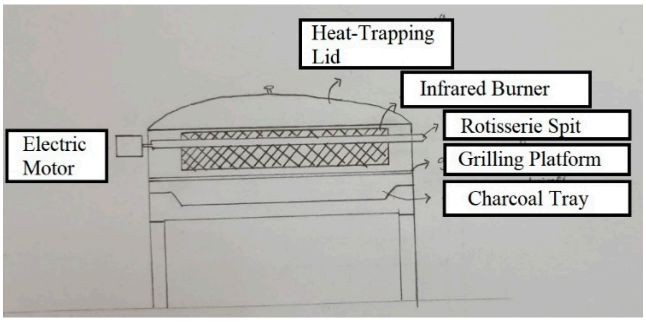
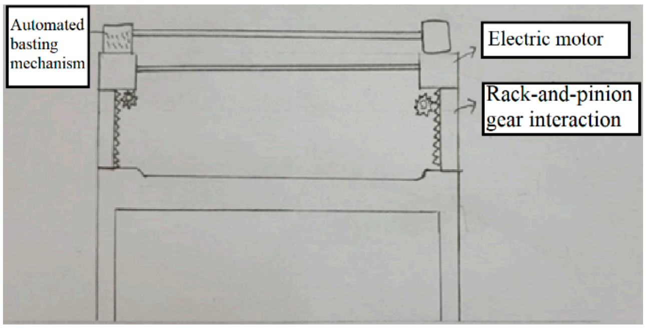
3.1. Concept Generation

This section includes the generation of new lamb rotisserie machine concepts. These concepts are created according to the features selected from patents, journal articles and existing products. These features are shown in Table 5. The features are deemed useful in potentially improving the productivity of conventional lamb-roasting machines and are adopted into several concepts. Table 6 shows the draft of all the concepts.

Table 5. A list of useful features.

Feature	Description	Comment	Sources
Spit Height Adjustability	Adjustability of the rotisserie spit height (distance between roast lamb and heat source). Can be achieved by pin joints/mechanism.	Important feature for temperature control.	[23,25]
Automatic Spit Rotation	The roast lamb is rotated as it is being roasted. Can be achieved by an electric motor/pulley system.	Very important feature for productivity.	[23,25]
Grilling Platform	A metal grill that is placed on top of a heat source to grill secondary items such as vegetables and smaller pieces of meat.	Good features for productivity. Eliminates the need for another apparatus for grilling.	[23,26,27]
Accessible Skewer	The skewer can be taken out from the stand easily for basting purposes.	Important feature for productivity.	[25]
Multiple Rotisserie Spits	Increased number of roast lamb output.	Very important feature for productivity. Able to increase productivity without changing the cooking method.	[12]
Lockable Wheels	Wheels at the base of the machine for portability.	Average for productivity.	[23,27]

Table 6. Draft of the concepts.

Concept	Draft
A	
B	
C	
D	

Concept A: This concept utilises a central bevel/mitre gear mechanism to rotate an array of lamb rotisserie stations. A pulley is used to rotate a long, central pinion gear, and as the mitre gear mechanism is engaged, the pinion gear drives the rotisserie spits of multiple lamb-roasting stations. This design aims to increase productivity by increasing the number of rotisserie machines without increasing the number of rotisserie spit actuators.

By using a central mitre gear mechanism, multiple rotisserie stations are driven by a motor. The number of rotisserie stations can be increased further by increasing the length of the pinion mitre gear.

Concept B: This concept includes a rack-and-pinion gear mechanism and a roller chain/sprocket mechanism. The rack-and-pinion gear is placed at the centre of the platform and is used to adjust the distance between the rotisserie spits and heat source. Multiple rotisserie spits are located on top of a platform. The platform is installed with a roller chain mechanism that is driven by an electric motor. The rotisserie spits are modified to include a sprocket near the handle. The sprocket interacts with the roller chain mechanism. As the roller chain moves in a linear and horizontal direction, the rotisserie spits are rotated due to the sprocket-roller chain interaction.

Concept C: Concept C aims to solve the productivity issue of the traditional lamb-roasting machine by replacing the charcoal-fired heat source with an infrared burner. Unsuch as charcoal fire, an infrared burner has a faster heat-up time and does not require maintenance to sustain the temperature of the heat source. An infrared burner is located at the back wall of the cooker's body, and a lid is used to prevent the escape of hot air from the cooker.

Concept D: Concept D intends to increase the productivity of a lamb-roasting station by installing an automatic basting mechanism. Basting is the action of applying marination to the lamb's surface to retain the meat's moisture, and it is done every 15 min. On average, a roast lamb takes about 3–4 h to cook from start to finish, which means that a user of the traditional lamb-roasting device would have to baste the lamb about 6–8 times throughout a single cooking session. The automatic basting mechanism solves this problem of incessant basting, which potentially reduces the workforce, thereby increasing productivity.

3.2. Concept Selection

The concept selection is done through a scoring process. The concepts are rated numerically using scales relative to a benchmark. The following steps are taken to conduct the scoring process.

1. A set of criteria is created.
2. A reference design is identified. In this case, a typical lamb rotisserie machine is chosen as a reference.
3. Weights are designated to each individual criterion.
4. The different concepts are evaluated and assigned ratings.
5. The weighted score and rank of the concepts are determined.

The list of selection criteria includes productivity, cost-effectiveness, ease of storage and portability. The justifications for using each of the selection criteria are as follows:

1. Productivity. The core purpose of this study involves developing an inventive solution to improve the productivity of conventional lamb-roasting solutions. Based on this core purpose, the concept selection should emphasise productivity. Hence, a 50% weightage is allotted to the productivity criterion.
2. Ease of storage. The demand for roast lamb fluctuates all year round. It is somewhat important for the solution to be easily stored or possess space-saving attributes so that it can be kept away easily when not in use. Thus, a weightage of 10% is assigned to this selection criterion.
3. Portability. Lamb rotisserie cooking is mostly done outdoors due to the high temperature and burning of charcoal. In view of this condition, it is somewhat important for the solution to be portable for the user to conveniently move it around (for instance, from indoors to outdoors). Hence, a weight of 10% is allocated to this selection criterion.
4. Cost-effectiveness. Every invention needs to be cost-effective, as it improves manufacturability and start-up costs. Therefore, a weight of 30% is given to this selection criterion.

Table 7 shows the scoring process. The ratings were solely proposed by the main author based on his specific experience and knowledge of various rotisserie machines, with over 4 years of research experience in this area of study. In reference to the main author's superior design sense in this specific area, the co-authors of this study concurred with the ratings and rankings provided by the main author. This process has been used and published in previous studies [38–40]. The scores range from 1 to 5. The description for each numerical value is as follows:

- ➢ Score 1: much worse than reference;
- ➢ Score 2: worse than reference;
- ➢ Score 3: matches reference;
- ➢ Score 4: better than reference;
- ➢ Score 5: much better than reference.

Table 7. Scoring of the concepts.

Criteria	W (%)	Concept									
		Concept A		Concept B		Concept C		Concept D		Reference	
		R	WS	R	WS	R	WS	R	WS	R	WS
Productivity	50	4	2.0	4	2.0	4	2.0	3	1.5	3	0.6
Ease of Storage	10	3	1.8	3	0.3	3	0.3	3	0.3	3	0.3
Portability	10	2	0.2	3	0.3	2	0.2	2	0.2	3	0.6
Cost-Effectiveness	30	4	1.2	4	1.2	3	0.9	1	0.1	3	0.9
Total Score		5.2		5.3		3.4		2.1		2.4	
Rank		2		1		3		5		4	
Continue?		No		Yes		No		No		-	

Notes: W—Weight; R—Rating; WS—Weighted score; Reference—Conventional lamb-roasting machine.

The scoring results show that concept B ranked first among the other concepts, with a total weighted score of 5.3. This design excels in the productivity aspect as it uses multiple spits for the machine to produce multiple roast lambs. It is also more cost-effective than the other concepts as it allows for multiple rotisserie spits to be actuated with only 1 electric motor, making it an inexpensive option with regard to its production. Hence, concept B is selected as the finalised design for further development.

3.3. Material Selection Standards in the Food Industry

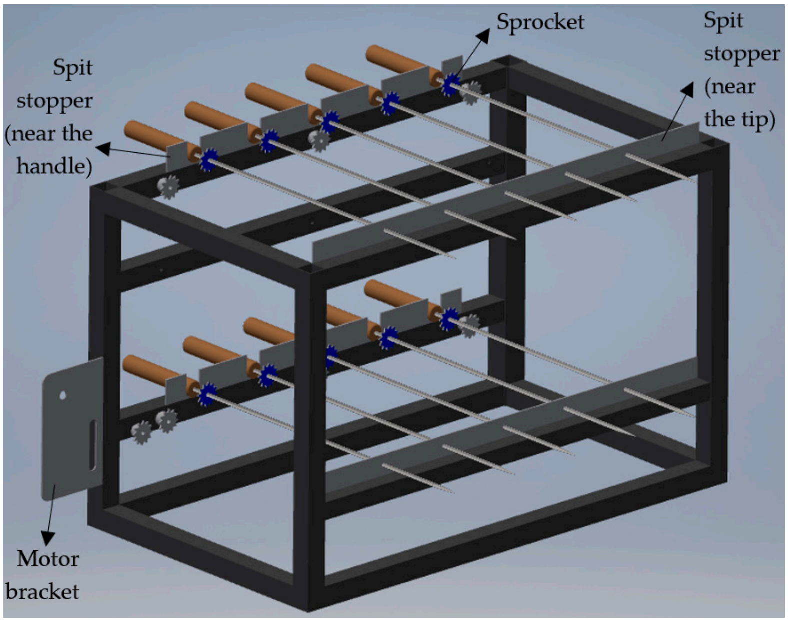
In food manufacturing, cleanliness and hygiene are of paramount importance. The most effective materials for food processing equipment include non-corrosive and inert materials [41]. The material chosen for this study needs to have high heat resistance as charcoal burns at temperatures exceeding 1100 °C [42]. In comparison, the melting point of iron is approximately 1200 to 1550 °C. The most common form of corrosion is oxidation, where oxygen reacts with a metal, usually in the presence of water, to produce more non-reactive material such as rust. For ferrous metals, iron and steel, rust ruins the surface quality and structural stability of the equipment. However, for other types of metals, oxidation may be beneficial [43].

Stainless steel is used widely in food manufacturing. It is characterised by the addition of chromium (at least 10.5% of the total composition). Chromium is highly reactive to oxygen-enriched environments and quickly forms a strong passivated barrier on its outer surface. This barrier is highly resilient and protects the internal structures from further corrosion [44].

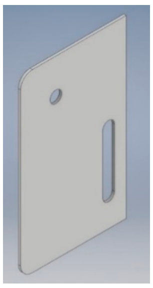
All components in contact with food during machine operations have to abide by the above-mentioned constraints. Apart from these constraints, the material selected for the base of the machine also has to be strong enough to withstand the total load on the entire machine. Due to its cost, heat resistance, strength, corrosive resistance, ease of machining, availability and conventional use in food manufacturing equipment, stainless steel is chosen for further design simulations.

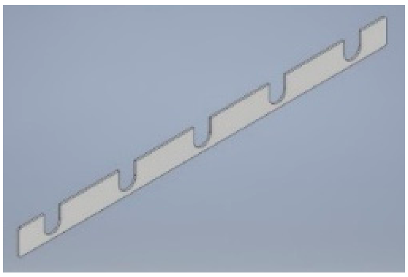
3.4. Design Drawing of Modified Concept

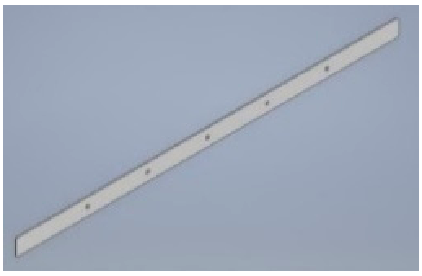
The design drawing and optimisations are presented in the data availability sheet. After careful considerations, the rack and pinion gear mechanism used for the height adjustment of the rotisserie spits (distance from heat source) is eliminated. Instead, a second platform is created to support more rotisserie spits for enhanced productivity. The modified design supports up to 10 rotisserie spits. Figure 1a shows the 3D drawing of the modified design's complete assembly. A groove is made at the side of the motor bracket in Figure 1b so that a sprocket can be installed on top to guide the movement of the roller chain. Therefore, the tension of the roller chain is adjustable for maintenance or emergencies. The space between the rotisserie spits is about 300 mm wide.



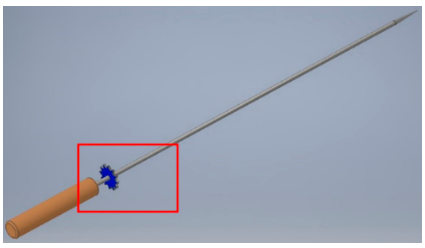
(**a**) The assembly after design modification


(**b**) Motor bracket


(**c**) Spit stopper (near the handle)


(**d**) Spit stopper (near the tip)


(**e**) Sprocket


(**f**) Spit with sprocket

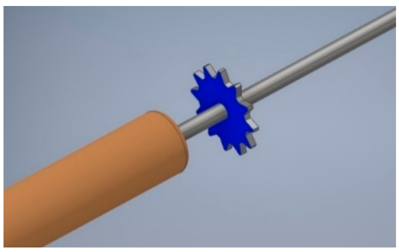

(**g**) Spit with sprocket (Enlarged)

Figure 1. A 3D drawing of the complete assembly and parts.

During the roasting process, the rotisserie spits will rest on top of the moving roller chain. In order to prevent the translational motion of the spits, a stopper must be included. Figure 1c,d shows the isometric views of the rotisserie spit stopper placed near the rotisserie spit handle and near the tip of the rotisserie spit. Figure 1e shows the 3D drawing of the sprocket. Figure 1f,g shows the rotisserie spit assembled with the sprocket and an enlarged view of the sprocket on the spit. The sprocket will rest on the moving roller chain and facilitate the rotation of the spit.

3.5. Simulation on Modified Concept

The load on the design is represented by the mass of the rotisserie spits and the lamb. Each spit weighs 2.761 kg, and each lamb weighs 23.6 kg. During the operation, each rotisserie spit rests on the frame at 2 opposing points. Thus, each load component represents half of the load composed of the rotisserie spit and lamb, which is around 129.3 N. The material assigned to the frame is steel.

Figure 2 shows the maximum displacement of the frame, which occurs in the middle of the upper platform's horizontal column as indicated. The maximum displacement is 0.249 mm, which happens at the horizontal bars on which the rotisserie spits are positioned. The minimum displacement is 0 mm, which happens at most of the frame columns where no static force is exerted. The maximum displacement of 0.249 mm is insignificant in relation to the length of the horizontal column, which is 600 mm. In addition, the maximum equivalent strain from the analysis is 0.00006052 mm/mm or 60.52 $\mu\epsilon$, which is reflective of the small displacement obtained.

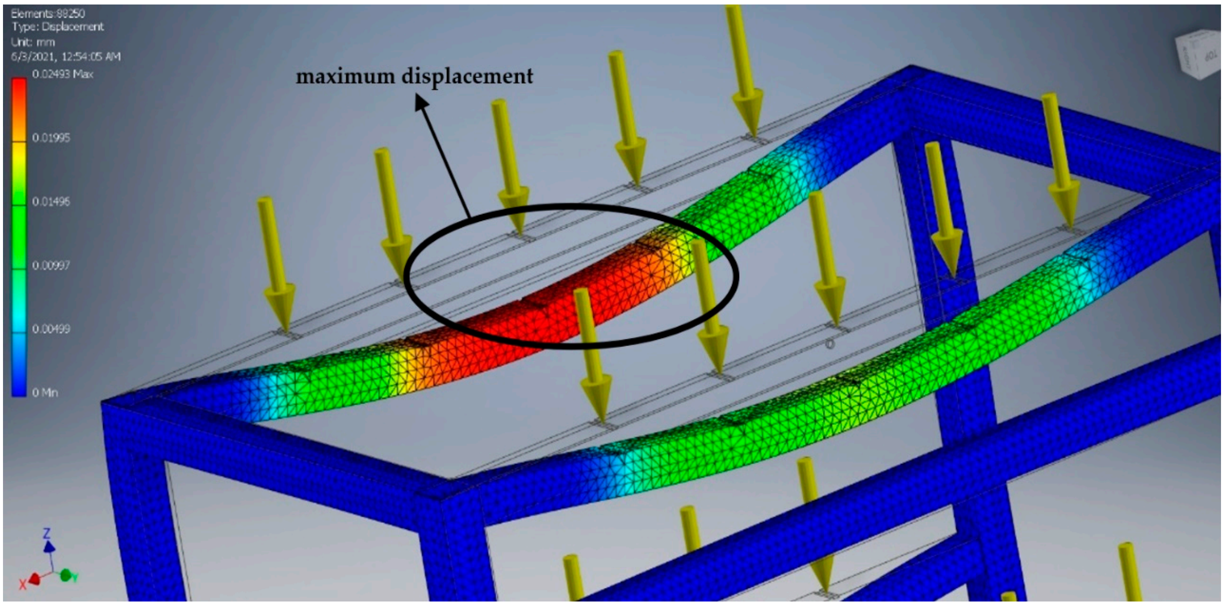


Figure 2. Stress simulation results for the frame (displacement).

Figure 3 shows the von Mises stress analysis. The maximum von Mises stress acting on the frame is 8.16 MPa. Most of the stress concentrates on the edge of the frame, where the surface area is the smallest. The von Mises stress exerted on the frame does not exceed the tensile strength of steel which is approximately 370 MPa.

The safety factor remained as 15 despite optimisations in the design's column dimension (as per the data availability sheet). This design is still considered over-engineered. A change of material might be able to reduce the safety factor to an appropriate level. However, it was established that stainless steel is the preferred material for food production equipment due to its high corrosion resistance, heat resistance and ease of maintenance. This preference is also recommended under the guidelines of the FDA [45]. Considering the preference of using stainless steel coupled with a concern of exceeding the slenderness ratio, which creates risks in buckling and also the time constraint of completing the project, the researchers decided to proceed with the present design and material.

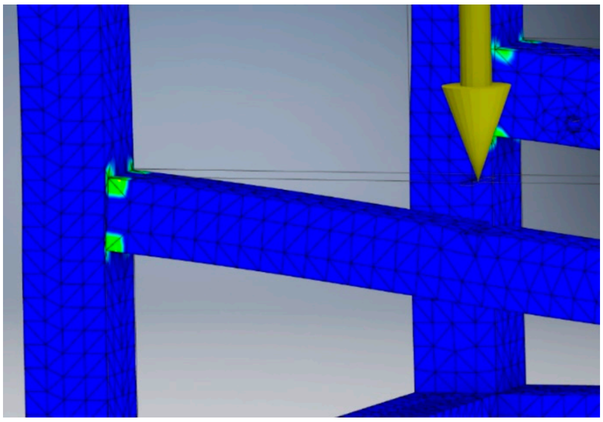


Figure 3. Stress simulation for the frame (von Mises stress).

3.6. Prototype Fabrication

3.6.1. Prototype Scaling

Due to project cost constraints, the prototype design is scaled down for fabrication. Table 8 shows the dimension comparison of the full-size lamb rotisserie machine and the prototype lamb rotisserie machine. The frame of the prototype is scaled down at a ratio of 2.25:1 in height, 4:1 in length, and 3:1 in width.

Table 8. Size comparison between full-size and prototype lamb rotisserie machine.

Dimension	Full Size (mm)	Prototype Size (mm)
Height	900	400
Length	1400	360
Width	1900	600

3.6.2. Parts Procurement

Based on the optimal dimensions and specifications, the researchers identified that the 12SB12 sprocket and the RS25 roller chain are suitable parts to be used in the proposed lamb rotisserie machine. The motor used is the SPG30-120 K 12 V electric motor [46]. This motor is chosen for its low RPM as the prototype requires a slow rotational speed and high torque.

3.6.3. Fabrication of Frame

The metal frame of the prototype is made out of 25 mm rectangular mild steel columns. The mild steel columns were purchased from the subcontractor's warehouse. Table 9 shows the assortment of mild steel columns required to make up the frame of the prototype. The machinist separated the mild steel columns into 4 pieces of 400 mm columns, 4 pieces of 360 mm columns and 6 pieces of 620 mm columns.

Table 9. Dimension and amount of mild steel columns required.

Dimension of Mild Steel Column (mm)	Amount
400	4
360	4
600	6

3.7. Test Plan

There are 3 main experiments conducted to test the prototype's functionality. The first two experiments focus on the productivity of the prototype, while the remaining experiment investigates the temperature stability or heat distribution when the prototype is in use. Two set-ups will be used in this experiment, one being the experimental set-up and another being the control set-up. The proposed lamb rotisserie machine is used for both set-ups. When the prototype is utilised at its full capacity (all 10 rotisserie spits used), it is a representation of the experimental set-up. When the prototype is utilised at its limited capacity (only 1 rotisserie spit used), it is a representation of the control set-up. In the experiments, the controlled variable is roasting time and the number of cooked lamb meat produced. Figure 4a,b shows the experimental and control set-up, respectively.

(**a**) The experimental set-up (**b**) The control set-up

Figure 4. The prototype set-up for the experiments.

In this project, two experiments are conducted to test whether the prototype improves productivity in comparison with a regular lamb-roasting machine. The experiments are (1) the roasting output test and (2) the roasting time test. Minitab 17 is used to run the two-sample *t*-test, Mann–Whitney U test and other basic statistical calculations such as mean and standard deviation.

The main researcher (main author) gave his written informed consent prior to the experiments. All procedures and protocols have been approved by the Research Ethics Committee (REC) from the Technology Transfer Office (TTO) of Multimedia University. The research ethics approval for the project has been granted with the approval number EA0052021 on 26 February 2021, and the approval letter has been endorsed by the TTO Director-cum-REC Secretariat of the university.

3.7.1. Experiment 1: Roasting Output Test

This experiment compares the roasting capabilities (amount of roasted meat produced in a total fixed time of 16 min) between the experimental set-up and the control set-up. The range of temperatures at which the meat was deemed to be successfully cooked is 60–71.11 °C (140–160 °F). The internal temperature of the meat is measured using a meat temperature probe. The procedures used for the experimental set-up are as such:

1. The lamb meat is cut into small chunks with a uniform thickness of 20 mm in the cross-section.
2. Ten pieces of lamb meat are inserted into the ten separate rotisserie spits and set aside.
3. The charcoal is ignited with a charcoal starter and then placed onto the charcoal tray of the prototype.
4. All rotisserie spits are placed onto their respective slots.
5. The timer is started as soon as the motor of the prototype is started.
6. The timer is paused after 16 min. The cooked pieces of meat are taken out, and another batch of raw meat is inserted into the rotisserie spit.

7. The internal temperature of the cooked meat is measured immediately by inserting the meat internal temperature thermometer into the lamb meat for 5 s.
8. The timer is resumed when the new batch of raw meat is placed onto their respective slots.
9. Steps 6 and 7 are repeated after every interval of 16 min until the timer reaches the total time fixed time of 80 min.
10. The number of successfully cooked meat is recorded.

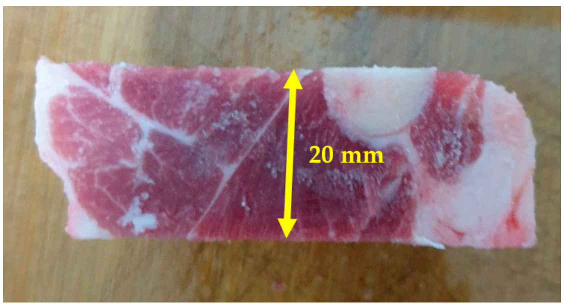
The procedures used in the control set-up are similar to the ones used in the experimental set-up. The only difference for the control set-up is in step 2, whereby instead of using 10 pieces of lamb meat and 10 separate rotisserie spits, the researcher only needs to use 1 piece of lamb meat and 1 rotisserie spit.

3.7.2. Experiment 2: Roasting Time Test

This experiment compares the difference in roasting time per unit when producing successfully cooked meat with the experimental and control set-up. Similar to experiment 1, the researcher only roasts 1 piece of meat for the control set-up. In order to observe the roasting time per unit for the experimental set-up, the researcher cooks 2 pieces of meat simultaneously. The procedures used for the experimental set-up are as such:

1. The lamb meat is cut into small chunks with a uniform thickness of 20 mm in the cross-section.
2. Two pieces of lamb meat are inserted into two separate rotisserie spits and set aside.
3. The charcoal is ignited with a charcoal starter and then placed onto the charcoal tray of the prototype.
4. The rotisserie spit is placed onto their respective slots.
5. The timer is started as soon as the motor of the prototype is started.
6. The internal temperatures of the meat are measured every 4 min by inserting the meat internal temperature probe into the lamb meat for 5 s.
7. A piece of lamb meat is taken out of the prototype as soon as its internal temperature registers at least 60 °C or 140 °F.
8. The timer is stopped once the two pieces of meat have been successfully cooked.

The procedures used in the control set-up are similar to the ones used in the experimental set-up. The only difference for the control set-up is in step 2, whereby instead of using 2 pieces of lamb meat and 2 separate rotisserie spits, the researcher only needs to use 1 piece of lamb meat and 1 rotisserie spit. Figure 5a shows the standardised thickness for the lamb meat, and Figure 5b shows the meat internal temperature thermometer.



(**a**) Thickness of all lamb meat standardised to 20 mm

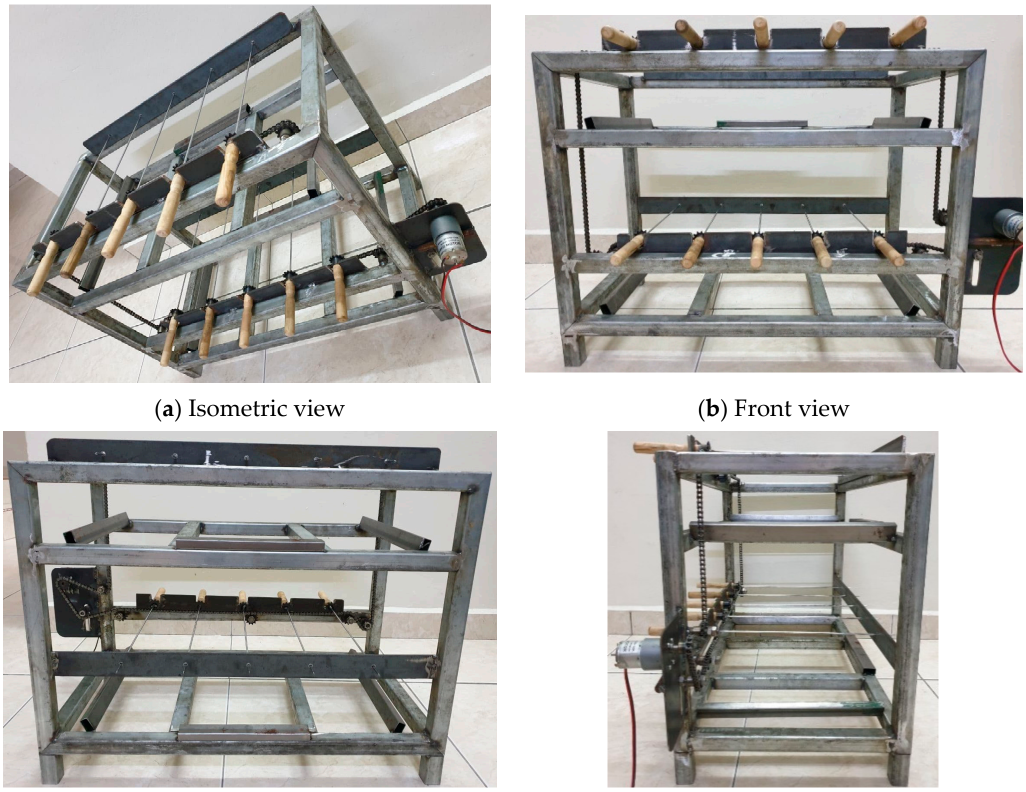
(**b**) Meat internal temperature thermometer

Figure 5. The lamb meat and thermometer.

4. Results and Discussion

4.1. Finalised Prototype

The prototype for the automated multi-spit lamb rotisserie machine possesses two platforms, each accommodating up to five rotisserie spits. All the spits are automatically rotated on a roller chain which is moved by an electric motor. The inventive configuration of the sprocket-roller chain mechanism allows the entire machine to be actuated by only 1 electric motor. Figure 6a–d shows the isometric, front, back and side view of the prototype.



(**a**) Isometric view (**b**) Front view

(**c**) Back view (**d**) Side view

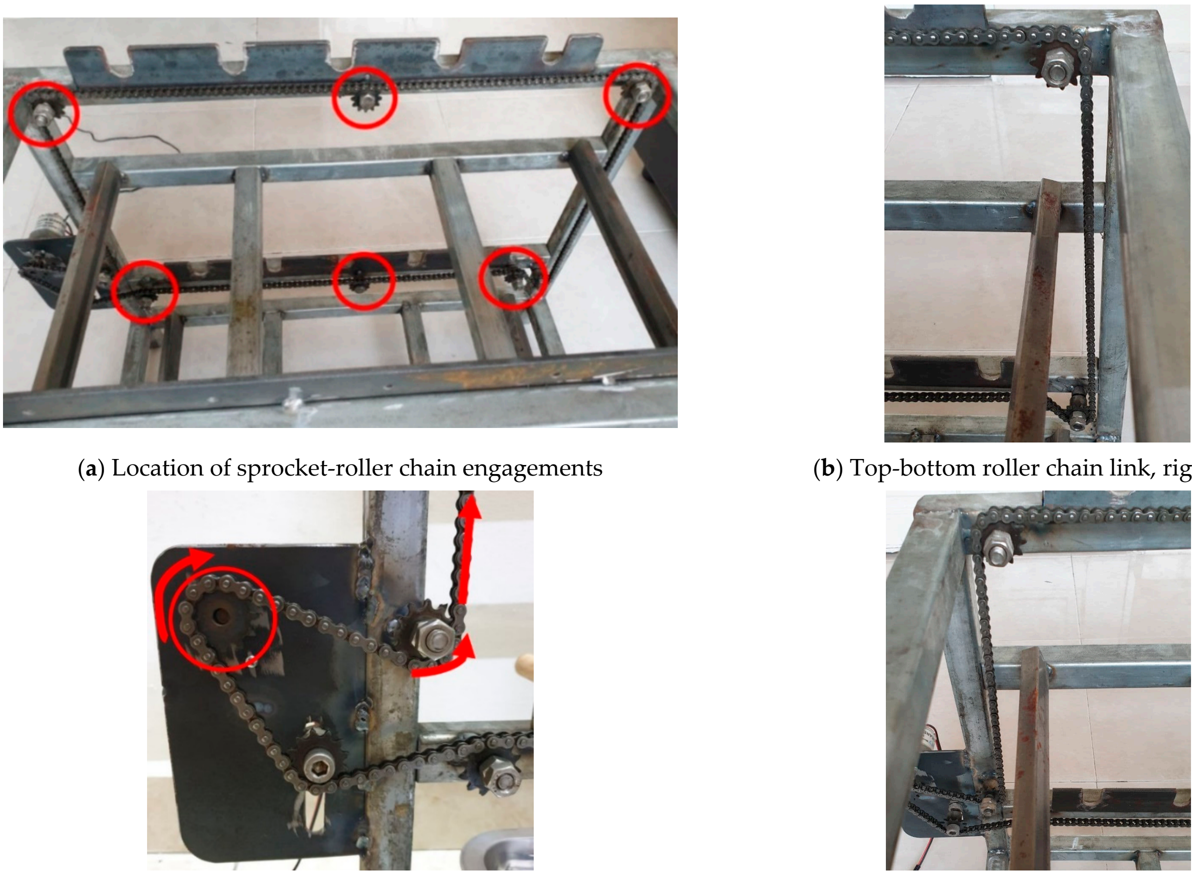
Figure 6. The finalised prototype.

The total weight of the entire rotisserie machine with all parts and components considered is 37.5 kg. This weight is considered moderate when compared to commercial lamb rotisserie machines in the market. Commercial-grade single spit lamb rotisserie devices weigh from 8 to 70 kg [25,47,48].

4.2. Sprocket-Roller Chain Mechanism

In Figure 7a, the circled locations show the freely rotating sprockets. There are 6 freely rotating sprockets installed onto the frame of the prototype. These sprockets are installed at their specific locations to hold the roller chain in place.

Figure 7b–d shows the sprocket configuration that creates a link from the top platform to the bottom platform. These links allow the rotational movement from the bottom platform to be transmitted to the top platform, thus reducing the need for individual electric motors for each platform. During the design phase of this project, the frame dimension and sprocket placement were designed to allow enough clearance for the movement of the roller chain. In Figure 7c, when the motor is turned on, the circled sprocket will rotate clockwise and move the entire roller chain in the direction of the arrows.



(**a**) Location of sprocket-roller chain engagements (**b**) Top-bottom roller chain link, right side

(**c**) Sprocket configuration on the motor bracket (**d**) Top-bottom roller chain link, left side

Figure 7. Sprocket-roller chain mechanism.

Figure 8a shows the rotisserie spit of the prototype. The rod of the rotisserie spit is made out of stainless steel, while the handle is made out of wood. A 25SB12 sprocket is installed on the top of the handle. As shown in Figure 8b, the sprocket on the rotisserie spit will rest on top of the roller chain. As the roller chain moves, the sprocket teeth move along the slots of the roller chain, causing the rotisserie spit to rotate concurrently. Table 10 shows the specification of the prototype.

Table 10. Specifications of the prototype.

Part	Specification
Frame dimensions	600 (L) × 400 (H) × 360 (W) mm
Frame material	Mild steel
Frame weight	10.9 kg
Number of sprockets	10
Sprocket specification	25B12
Roller chain length	10 ft
Motor	Speed: 38 RPM Torque: 0.49 Nm
Spit	295 cmm

(**a**) Rotisserie spit with a sprocket (**b**) Spit-roller chain mechanism

Figure 8. The rotisserie spit used for the spit-roller chain engagement.

4.3. Results and Discussion of Experiments

The experimental set-up includes the use of the automated multi-spit lamb rotisserie machine prototype, while the control set-up includes the use of the same prototype in the capacity of a single-spit rotisserie machine.

Roasting Time Test

This experiment aims to assess the time taken to produce one unit of successfully roasted lamb meat. The time is recorded when the internal temperature of the meat reaches 60 °C. Two pieces of lamb meat are roasted at the same time for each batch of the experimental set-up, whereas only one piece of lamb meat is roasted for each batch of the control set-up. The average time taken to successfully roast the lamb meat for each batch under the experimental set-up can be calculated as such:

$$t_E = \frac{t_A + t_B}{2} \quad (1)$$

where t_A —time taken to roast meat A per batch under the experimental set-up; t_B—time taken to roast meat B per batch under experimental set-up; t_E—average time taken to roast meat A and B per batch under experimental set-up.

The average roasting time for the experimental and control set-up is also compared. There are two pieces of lamb meat roasted for each batch in the experimental set-up (N_E = 2) and one piece of lamb meat roasted for each batch in the control set-up (N_C = 1). The roasting time per unit for the experimental and control set-up can be calculated using Equations (2) and (3). The data collected will be available in the data availability sheet.

$$r_E = \frac{t_E}{N_E} = \frac{t_E}{2}$$

$$r_E = \frac{t_E}{2} \quad (2)$$

$$r_C = \frac{t_C}{N_C} = \frac{t_C}{1} = t_C$$

$$r_C = t_C \quad (3)$$

where r_E—roasting time per unit for each batch under experimental set-up (s/unit); N_E—number of meat roasted per batch under experimental set-up; r_C —roasting time per unit for each batch under control set-up (s/unit); t_C—average time taken to roast meat per batch under control set-up; N_C —number of meat roasted per batch under control set-up.

Sample Size Estimation and Normality

Before a two-sample *t*-test is conducted, it is essential to inspect if the sample size is adequate. Using the pooled standard deviation, mean difference and a power value of 80%, the sample size is estimated to be 2 (see Table 11). The sample size of the current dataset is 10, which exceeds the sample size calculated by Minitab 17, indicating that the current sample size is sufficient for this study.

Table 11. Sample size estimation by Minitab.

Parameter	Value
Pooled standard deviation	9.524
Mean difference (s/unit)	476.3
Target power	80%
Sample size	2
Actual power	100%

For the assumption of normality, the Ryan–Joiner normality test proved that the data are not significantly different from a normal distribution ($p > 0.05$). Thus, the dataset is appropriate for further parametric tests. The F-test and Levene's test also verified that there is a significant difference in the variance of the dataset between the experimental and control group ($p < 0.05$). Hence, the *t*-test used would apply the assumption of unequal variance.

Two-Sample *t*-Test

The following hypotheses are used for the roasting time test.

- Null Hypothesis, H_{0a}: There is no significant difference in the roasting time between the control and experimental set-up ($p > 0.05$).
- Alternative Hypothesis, H_{1a}: There is a significant difference in the roasting time between the control and experimental set-up ($p < 0.05$).

Table 12 shows the mean and standard deviation of the roasting time for the experimental and control set-up. The results show that the experimental set-up uses a shorter roasting time than the control set-up. It is important to note that the unit for roasting time is seconds/unit (s/unit), which measures the amount of time it takes to cook one piece of meat to the internal temperature of 60 °C. The experimental set-up uses a mean roasting time of 497.3 s/unit, while the control set-up uses a mean roasting time of 973.6 s/unit.

Table 12. Statistics for the roasting time per unit.

Set-Up	Mean (s/Unit)	StDev
Experimental	497.3	7.64
Control	973.6	20.5

Notes: N = 10; StDev—standard deviation.

According to the results in Table 13, there is a significant difference in the roasting time between the experimental and control group ($t(11) = -66.62$, $p < 0.05$). The results indicate that the automated multi-spit lamb rotisserie machine prototype is significantly more productive than a regular lamb-roasting set-up which only produces one roast lamb at a time. Therefore, H_{1a} is supported.

Table 13. Two-sample *t*-test results.

Parameter	Value
Estimate for difference	−476.35
95% CI for difference	(−491.59, −461.11)
t-value	−68.79
p-value	0.000
DF	11

Roasting Output Test

In this experiment, both the experimental and the control set-ups are used to roast lamb meat in five cooking sessions. The aim is to roast as much lamb meat as possible within each cooking session which lasts for 16 min. For the experimental set-up, all

10 rotisserie spits are used to cook the pieces of lamb meat. The control set-up only used one rotisserie spit to cook one piece of lamb meat. After roasting for 16 min, all the pieces of lamb meat are removed from the rotisserie spits. The internal temperature for each meat is measured. If the internal temperature of a piece of lamb meat is within the range of 60 °C to 71.11 °C, it is considered successfully cooked. Otherwise, the particular sample is rejected. In other words, only cooked meat that is classified as medium rare, medium well, medium and well done are considered successfully cooked. The ones that are classified as extra rare, rare and overcooked are considered not successfully cooked.

Table 14 shows the summary of data from the roasting output test. The results show that the experimental group is able to produce an average of eight successfully roasted lamb meat while the control group is only able to produce an average of one successfully roasted lamb meat for all five cooking sessions. All in all, the experimental set-up produces an average surplus in roast meat output of 700% as compared to the control set-up (see Table 15).

Table 14. A summary of data from the roasting output test.

Set-Up	Average Roast Meat Output (Unit)					Mean (Unit)
	a	b	c	d	e	
Experimental	7	8	8	9	8	8
Control	1	1	1	1	1	1

Notes: a, b, c, d, e—Cooking sessions.

Table 15. Surplus roast meat output (experimental versus control set-up).

Cooking Session	Roast Meat Output Surplus (%)
1	600
2	700
3	700
4	800
5	700
Mean	700

Productivity issues that are inherent in regular lamb-roasting machines are partly because the regular machine is only able to produce one roast lamb at a time. The roasting time and output tests proved that the present study's automated multi-spit lamb rotisserie machine could significantly increase the amount of roast lamb produced and significantly shorten the overall time taken to produce roast lamb.

The concept used in this study is akin to the design of an existing product known as the 1425.4SMiE Special Market chicken rotisserie machine [12]. This product is able to accommodate multiple whole chickens (up to 24 units) in one cooking session and also aims to improve productivity.

While this product possesses a similar aim, its focus is mainly on producing roast chicken. In addition, the way it produces multiple roasts at a time is also different from the way the prototype of this study functions. For instance, the 1425.4SMiE emphasises roasting multiple whole chickens inserted in a single spit, while the prototype of this study emphasises roasting multiple spits of a whole lamb. The inventive solution used by this study (i.e., using the sprocket and roller chain) also makes the current prototype unique apart from being productive.

4.4. Temperature Stability Test

When the prototype runs at its full capacity (i.e., 10 rotisserie spits running concurrently), it is noticed that at least one unsuccessfully roasted meat would be produced, be it undercooked or overcooked. This issue is possibly due to the uneven heat exposure caused by factors such as the distance of the meat to the heat source and unregulated air flow.

Therefore, it is essential to perform an overall temperature stability test using the temperature dataset collected from the previous experiment. Since the temperature dataset violated the assumption of normality, the Mann–Whitney U test (a non-parametric test) is used to determine if the temperature distribution differs significantly between the experimental and control set-up. The following hypotheses are used.

- Null Hypothesis, H_{0b}: There is no significant difference in the temperature distribution of the meat roasted with the experimental set-up as compared to the control set-up ($p > 0.05$).
- Alternative Hypothesis, H_{1b}: There is a significant difference in the temperature distribution of the meat roasted with the experimental set-up as compared to the control set-up ($p < 0.05$).

In this analysis, the temperature distribution is determined by the internal temperature of the lamb meat after being roasted for 16 min (as per the roasting output test procedures). As shown in Table 16, the Mann–Whitney U test indicated that the temperature of the experimental group (median = 150.1 °F) does not significantly differ from the temperature of the control group (median = 151.5 °F), U = 1370, $p = 0.3878$.

Table 16. Results of median calculated from Mann-Whitney U test.

Set-Up	N	Median (°F)	U	*p*-Value
Experimental	50	150.1	1370	0.3878
Control	5	151.5		

In summary, the null hypothesis, H_0, is accepted, and the analysis confirms that the overall temperature distribution for the experimental group is considered stable even with a few samples being unsuccessfully roasted for some cooking sessions.

4.5. Temperature Outlier Tests

Although the overall meat temperature is stable with the experimental set-up, the prototype still consistently produced around 1 to 2 pieces of unsuccessfully cooked meat. It is noticed that the unsuccessful outputs come from the rotisserie spits located at the sides of the rotisserie machine. In order to verify this observation, four tests are conducted to compare the roast meat temperature in different rotisserie spit locations.

As shown in Figure 9, each rotisserie spit is assigned a number. The tests aim to identify if the meat from spits 1, 5, 6 and 10 have significantly different temperatures than the meat from spits 3 and 8 after being roasted for 16 min (as per the roasting output test procedures). Spits 3 and 8 are selected as references since there are normally no defects produced in these spit locations. Based on the location of the platforms, spits 1 and 5 are compared with spit 3, while spits 6 and 10 are compared with spit 8. Therefore, the hypotheses can be formulated as such:

- Null Hypothesis, H_{0c}: There is no significant difference in the internal temperature of the meat cooked for spits 1, 5, 6 and 10 as compared to spits 3 and 8 ($p > 0.05$).
- Alternative Hypothesis, H_{1c}: There is a significant difference in the internal temperature of the meat cooked for spits 1, 5, 6 and 10 as compared to spits 3 and 8 ($p < 0.05$).

Table 17 shows the *t*-test results for the temperature outliers. All of the meat cooked in spits 1, 5, 6 and 10 are found to register an internal temperature of less than 60 °C after being roasted for 16 min. The meat cooked in spits 3 and 8 registered internal temperatures of 60 °C and above. The tests show that there is indeed a significant difference in the internal temperature of the meat cooked for spits 1, 5, 6 and 10 as compared to spits 3 and 8 ($p < 0.05$). Hence, H_{1c} is supported.

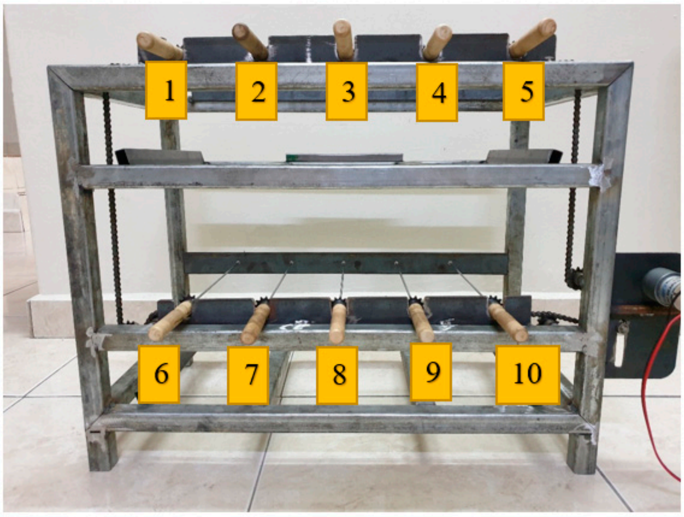


Figure 9. Rotisserie spit position numbering.

Table 17. *t*-test results for temperature outliers.

Parameters	Tests			
	Test 1–3	**Test 3–5**	**Test 6–8**	**Test 8–10**
Estimate for difference	−13.32	18.26	−13.12	19.14
95% CI for difference	(−24.17, −2.47)	(3.61, 32.91)	(−18.91, −7.33)	(9.82, 28.46)
t-value	−3.41	3.46	−5.23	4.73
p-value	0.027	0.026	0.001	0.001
DF	4	4	8	8

The analysis concludes that the heat exposure for the spits located at the sides of the prototype is not as uniform in comparison to the heat exposure for the spits located in the middle. In terms of productivity, such an uneven distribution of heat is undesirable. This issue may be due to the position of the charcoal fire during the experiments. Apart from controlling the air flow of the surrounding area, one way to mitigate the issue is to periodically refill the platform with charcoal for more consistent burning.

4.6. Brief Cost Analysis

Table 18 shows the price list for the parts that make up the prototype. The cost to produce one automated multi-spit lamb rotisserie machine is 216.30 USD/unit. The high costs of workmanship and material are due to the make-to-order nature of this project. If the product were to be mass-produced in the future, the total cost will decrease. Hence, if mass production were to take place, the material and workmanship costs can be reduced by about 40%. The high cost is also attributed to the price of the 25SB12 sprockets. The price of this particular sprocket is high due to the limited supply from the gear manufacturer. The 25SB12 sprocket is also not frequently manufactured. If this prototype were to be sold commercially, the cost of the parts would also reduce. Hence, if mass production were to take place, the sprocket costs can be reduced by about 50%. However, since this prototype is actually a scaled-down version, the total cost is still estimated at USD 216.30.

There are also other variable costs involved if the plan in the future is to set up a company that manufactures these lamb-roasting machines. The manufacturing of this prototype requires skilled workers for metal cutting and welding. The minimum wage in Malaysia is forecasted to be around 1200 MYR/month (around 286 USD/month) by the end of 2021 [49]. Hence, a total salary of 450 USD/month per skilled worker would be sufficient. The total salary of 2 skilled workers is around 900 USD/month, which is about 5.63 USD/hour (accounting for 40 h a week, for 4 weeks a month). If the company considers these skilled workers as permanent workers, the labour cost of making a single prototype becomes:

$$\text{Labour cost (USD)} = 216.30 - 23.50 + 5.63 = 198.43 \text{ USD}$$

Table 18. Price list for the product parts.

No.	Parts	Description	Unit	Unit Price (USD)	Total Cost (USD)
1	Mild steel column	400 mm	4	5.50	22
		360 mm	4	4.80	19.20
		620 mm	6	3.60	21.60
2	Sprocket	25SB12	18	3.80	68.40
3	High Torque Brushless Motor	SPG30-120 K, 12 V	1	9.70	9.70
4	Roller Chain	RS25, 10 ft	1	5.00	5.00
5	Workmanship	Professional welding, cutting	1	23.50	23.50
6	Welding cost	Material cost of welding	1	23.50	23.50
7	Charcoal briquettes	-	5	4.30	21.50
8	Charcoal tong	To pick and place hot charcoal	1	1.90	1.90
		Total			216.30

The USD 23.50 is subtracted as the original workmanship cost is not required (the workmanship is replaced with permanent skilled workers). By accounting for a 40% profit margin from the labour cost, the sales price of the automated multi-spit lamb rotisserie machine is estimated to be around USD 278. This price is reasonable for owners of small and medium enterprises (SMEs) who wish to ramp up the production of their roast lamb and compete in a larger market.

5. Conclusions

The aim of this study was to develop an automated multi-spit lamb rotisserie machine for improved productivity. In order to achieve this aim, reviews of patents, research articles and existing products in the market were done. The ideas and features extracted from the literature review were then utilised to design concepts that can be used to roast lamb for improved productivity. Apart from the conceptualisation stage, the development accounted for material selection, designing with CAD, stress analysis and prototype fabrication.

The productivity and performance of this solution were also tested with several usability experiments that measured the roasting time, roasting output and temperature stability. The data were analysed using *t*-tests.

5.1. Summary of Findings and Main Outcomes

The proposed lamb rotisserie invention was able to consistently outperform the conventional way of roasting lambs by a significant margin. In the roasting output test, the proposed invention was able to cook 700% more meat than a regular lamb-roasting set-up. In the roasting time test, the proposed invention was able to produce successfully cooked lamb meat 92.27% faster than the regular lamb-roasting set-up. There was also no significant difference between the proposed invention and the regular lamb roaster in terms of cooking temperature stability.

Lastly, the sales price for the proposed invention was estimated to be around USD 278, which is a reasonable price for lamb-roasting SME owners. In summary, the proposed invention successfully demonstrated the capability of enhancing the productivity and efficiency of producing roast lamb at a decent price with minimal changes to the system's roasting reliability. This achievement benefits not only SMEs in increasing lamb-roasting production capacity but also lamb-roasting machine designers and manufacturers that wish to gain a competitive edge over the existing lamb roaster market competition with this new invention.

5.2. Limitations

This study describes the novelty of the machine to escalate the productivity of roast lamb, which is not influenced in any way the origin of the meat [50], which could affect its texture or appearance when it is roasted. It is also believed that the quality of meat obtained for the experiment is consistent or standard, which is not affected by any external factors such as COVID-19, referring to a study carried out in China [51] or even any unfavourable economic landscape [52].

A limitation of this design is its uneven heat exposure. Through several *t*-tests using the temperature data from the roasting output test, it was found that the undercooked pieces of meat were consistent in number and often positioned close to the sides of the roasting pit. These positions included the rotisserie spits that were placed on slots that were farther away from the centre of the heat source compared to the other rotisserie spits. This uneven heat exposure caused some of the meat to be undercooked. Another limitation includes the lack of safe insulation around the frame of the body. During the roasting process, the metal frame of the prototype can get dangerously hot, exposing the risks of burning to the user.

Although proof of concept has been established in this study, an actual usability test and survey were not done among the relevant SMEs due to cost and time limitations in creating a full-scale prototype. The effects of thermal stress on the reliability of the prototype over time were also not studied in this paper.

5.3. Recommendations for Future Research

For an evenly distributed heat exposure, a thermometer can be embedded within the design to monitor the temperature of the charcoal fire and charcoal briquettes. The position of the charcoal briquettes could also be spread out evenly. In order to mitigate the risk of burning to the user, an insulation layer could be added to all vertical columns of the frame and all horizontal columns of the bottom platform as the user needs to be near these columns during the roasting process.

It would also be of interest to conduct design of experiments with the prototype to investigate various factors that can influence its performance and use more statistical analyses such as ANOVA, regression or paired samples *t*-tests. It is recommended that a full-scale prototype is developed in the future to account for further analyses and actual field testing amongst SMEs. One of the analyses can include the reliability analysis of the structure after being repeatedly subjected to high thermal stress over a period of time. Sensory analysis can also be performed to test the quality of the roast lamb produced by this machine.

Author Contributions: Conceptualization, X.W.C. and P.K.N.; data curation, X.W.C. and P.K.N.; formal analysis, X.W.C. and P.K.N.; investigation, X.W.C., P.K.N., R.J.N., J.A.Y. and Y.J.N.; methodology, X.W.C., P.K.N. and W.S.L.; project administration, X.W.C., P.K.N., R.J.N., W.S.L. and Y.J.N.; supervision, X.W.C. and P.K.N.; Validation, X.W.C. and P.K.N.; visualization, X.W.C.; writing—original draft, X.W.C., P.K.N., R.J.N. and J.A.Y.; writing—review and editing, X.W.C., P.K.N., R.J.N., J.A.Y., W.S.L. and Y.J.N. All authors have read and agreed to the published version of the manuscript.

Funding: The article processing charge for this manuscript is partially supported by Multimedia University (Reference number: MMU/RMC/PC/2021/26908).

Institutional Review Board Statement: The study was conducted according to the guidelines of the Declaration of Helsinki. All procedures and protocols have been approved by the Research Ethics Committee (REC) from the Technology Transfer Office (TTO) of Multimedia University. The research ethics approval for the project has been granted with the approval number EA0052021 on 26 February 2021, and the approval letter has been endorsed by the TTO Director-cum-REC Secretariat of the university.

Informed Consent Statement: The main researcher (main author) gave his written informed consent prior to the experiments.

Data Availability Statement: This project contains the following underlying data: Data Availability Sheet.docx (dataset used for the design drawing, optimisation, modifications, data collections and limitations). The data can be found at Figshare (doi:10.6084/m9.figshare.14994555). Data are available under the terms of the Creative Commons Attribution 4.0 International license (CC-BY 4.0).

Acknowledgments: This study was part of the main author's final year project for his B.Eng. (Hons) Mechanical degree. The researchers would like to thank the Faculty of Engineering and Technology, Multimedia University (MMU), for allowing this study to be carried out. The researchers would also like to thank Norhidayah Mohamad for providing some useful comments during the main author's project presentation. Special thanks go to the Research Ethics Committee and Technology Transfer Office members of MMU for granting the researchers with ethical clearance to conduct this study. The researchers are exceptionally grateful to Chiew Fen Ng for her constructive criticism of the manuscript. Finally, the researchers also thank the anonymous reviewers for their valuable comments.

Conflicts of Interest: No potential conflict of interest was reported by the authors.

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