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A TRIZ-Integrated Conceptual Design Process of a Smart Lawnmower for Uneven Grassland

Chun Quan Kang, Poh Kiat Ng * and Kia Wai Liew

Faculty of Engineering and Technology, Multimedia University, Jalan Ayer Keroh Lama, Bukit Beruang, Melaka 75450, Malaysia

* Correspondence: pkng@mmu.edu.my

Abstract: Existing smart lawnmowers, while convenient to use, have significant limitations, such as a lack of manoeuvrability on uneven agricultural grassland (constraint 1), high charging frequency (constraint 2) and low local market penetration (constraint 3). Although the effectiveness of the theory of inventive problem solving (TRIZ) has been demonstrated in several design studies, there also seems to be a lack of research addressing the design difficulties of smart lawnmowers using this method. With the use of the TRIZ method, this study seeks to conceptually design a smart lawnmower for uneven grassland. Tools from TRIZ were used, including cause-effect chain analysis, technical contradictions, physical contradictions, and substance field modelling. In developing a design concept, constraints were solved by inventive principles, separation strategies and standard inventive solutions. For constraint 1, the following solutions were chosen with the appropriate principles: using larger wheels (#17, another dimension: using a second or third dimension), a pivot design (#30, flexible shell: replacing rigidity with flexibility and movability) and replacing the motor with one that has more power or torque. For constraint 2, the following solutions were chosen: to reduce weight, add holes in the mower housing (#31, porous materials: making an object porous or adding porous elements) and attach a solar panel to recharge batteries with solar energy (#28, mechanical substitution: using electric, magnetic or other fields to interact with object). Using other materials or technologies to minimise costs (#13, the other way around: using the opposite way) and a modular design concept to reduce maintenance costs (#1, segmentation: dividing an object into independent parts) were the chosen ways to solve constraint 3. Conceptualisation and design analysis were also performed. Although the effectiveness of the concept is unclear, these suggestions are supported by previous research and could potentially solve some of the problems with smart lawnmowers.

Keywords: TRIZ; design process; smart lawnmower; agriculture; conceptualisation; design analysis

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1. Introduction

At a time when more and more people around the world are living in cities, urban green spaces are becoming increasingly important. These spaces provide several benefits to the urban environment, such as sequestering carbon, stabilising dust and reducing the impact of the heat island on human psychological and physiological health. The maintenance of green spaces consists of a large number of steps, of which lawn mowing is one of the most expensive and time-consuming.

Lawn mowing involves trimming the grasses to a certain height for decorative, hygienic or sporting purposes [1]. The machines used for mowing lawns are called lawnmowers and are widely used in agriculture, gardening, landscaping, and the maintenance of green areas by the general public [2]. Various types of lawnmowers have been developed over the years, such as lawnmower blades, spiral cord grass trimmers, reel blade grass trimmers, lawnmowers equipped with an internal combustion engine and more, but these variants usually present challenges in terms of operating efficiency. Gas-powered lawnmowers are the most common and widely used mowers that consist of integrated mechanical and electrical systems. It offers high cutting performance but is relatively noisy and produces emissions that contribute to global warming [3].

With the help of the rapid development of technologies driven by the fourth industrial revolution, automation technologies have been introduced in many sectors, including agriculture and landscape maintenance, to provide efficient, functional services. Battery-powered smart lawnmowers have been developed to reduce the need for labour to mow lawns while reducing local emissions and noise.

A smart lawnmower can operate day and night without human intervention, saving a significant amount of time in maintaining the grassland. Daily mowing helps reduce the size of clippings and the problem of leftover clippings and their disposal. A smart lawnmower protects the user from contact with allergens and injuries as it does not produce polluting gases and is equipped with safety features [4]. According to Sportelli et al. [5], smart lawnmowers that operate on random paths have an intriguing potential to function in environments with many obstacles, such as agricultural fields.

A survey of business leaders in the United States shows that sales of service robots continue to grow at a rate of more than 30% per year. The International Federation of Robotics predicts that the area of personal use of service robots, which includes smart lawnmowers, will continue to expand to help solve service problems [6]. According to a market report published by Allied Market, the global smart lawnmower market was valued at USD 538 million in 2017 and is expected to reach USD 1437 million by 2025 [7]. The report also shows that the smart lawnmower market is mainly used by home users and seems to be growing rapidly in recent years. Grossi et al. [8] found that a lawn that is mowed with a smart lawnmower is of higher quality and uses less energy compared to a lawn that is mowed with a conventional rotary mower. Therefore, there is evidence that smart lawnmowers are a valuable tool for sustainable and efficient lawn management.

1.1. Problem Statement

Autonomous lawnmowers have already been developed on the market, such as the Robomow rx12, the Husqvarna Automower 105, the iRobot Terra and the Agrirobot. Each of these products has its main features that differentiate them from each other. For example, the Robomow rx12 advertises its simple "push and go" mowing system. The Husqvarna Automower 105 is able to work even on rainy days. The iRobot Terra has an intelligent mapping system that allows it to mow in a back-and-forth motion, improving its efficiency. The Agrirobot, which stands out from the rest by its appearance, has several charging methods, including inductive charging, both by contact and by solar energy (the ZCS Active Panel) [9].

However, there still seem to be some limitations with these robotic lawnmowers that can be further improved and modified through proper studies and design processes. Firstly, although these robots are rechargeable, most of them need to be recharged frequently [10]. Secondly, the design of these products is not considered cost-effective as most of them are high priced (about 1500 USD to 3500 USD), and the availability of these products in the local Malaysian markets is considered low as these mowers are considered sophisticated robots with main markets typically found in developed nations such as Germany and the United States. Therefore, these products cannot be found in ordinary or specialised DIY stores in Malaysia. Last but not least, due to their ordinary designs, smart lawnmowers are only suitable for flat lawns; otherwise, they can easily get stuck [11].

It seems that there are no studies that address the above challenges in the product design of smart lawnmowers. These include locomotion on uneven grassland, frequency of charging and availability in the local market. There also seems to be a lack of studies that apply the Theory of Inventive Problem Solving (TRIZ) in addressing the design challenges of smart lawnmowers, although the success of TRIZ has been demonstrated in various design studies [12–16].

This study investigates the underlying causes of the above problems and proposes potential design solutions to improve the overall performance of the smart lawnmower using the TRIZ method. The inventive solutions obtained from the TRIZ method are listed for screening and scoring. Several concepts are then generated from the synthesis of these useful features, and only one final concept is selected among the others after a thorough selection process. After the conceptualisation process, the design is analysed using finite element analysis.

It is important to note that the scope of this study relates to addressing the limitations of smart lawnmowers, which include high charging frequency, low availability of a similar product in the Malaysian market and the ability to operate on uneven grassland. This study does not address other aspects of smart lawnmowers, such as blade design or cutting efficiency, microcontroller and robot motion algorithm. Therefore, aspects that are beyond the scope of this study will be adopted from existing smart lawnmowers through benchmarking and an appropriate selection process.

In summary, this study aims to conceptually design a smart lawnmower using the TRIZ approach. This study is an extension of the standard conceptual synthesis of a previous study [11]. To achieve this aim, the following research questions (RQs) are posed.

RQ1: How can the limitations of a smart lawnmower be resolved using the TRIZ approach?

RQ2: How can TRIZ be integrated into the conceptual design process of a smart lawnmower?

1.2. Limitations in Smart Lawnmower Design

A smart lawnmower, as with any other robot, cannot replace a human doing the job perfectly. It may have many sensors that make it more intelligent, but it does not have the subjective eye and brain that an operator has. Therefore, there will be limitations that require the continuous improvement of these robots [3].

Firstly, a smart lawnmower is better suited to a level and smooth lawn with minimal slopes and holes. It can easily get caught in holes and cause a malfunction, so someone has to physically free it to restore its normal functions. In addition, the smart lawnmower can also get stuck in tall grass. Therefore, the grass on the lawn must be manually shortened to a certain height before the smart lawnmower can operate on the lawn [1].

Secondly, a smart lawnmower works slowly and cuts in random patterns, and as one might expect, it uses battery power all the time. If the grassland is large enough, there is a chance that the smart lawnmower's battery will run out before it has mowed the entire area. Therefore, it needs to be recharged frequently. This challenge does not make the lawnmower environmentally friendly, even if it does not use non-renewable resources such as fossil fuels as an energy source [17].

Last but not least, the availability of these products in the local Malaysian markets is considered to be low as these mowers are classified as sophisticated robots, with main markets often found in developed countries such as Germany and the United States. Therefore, these products cannot be found in ordinary DIY stores or specialised shops in Malaysia.

1.3. Smart Lawnmower Design

A smart lawnmower is an autonomous robot that cuts grass to the desired height. Basic design considerations for a smart lawnmower include its configuration, cutting blade, sensors and additional features.

1.3.1. Configuration

Almost all existing robotic lawnmowers for households use two drive wheels with one or two trailing wheels. The exception is the LawnBott Spyder LB1200, which has two pairs of overlapping wheels, and more industrial lawnmowers that can use armoured tracks or a combination of tracks and wheels [18]. Possible configurations are shown in Figure 1.

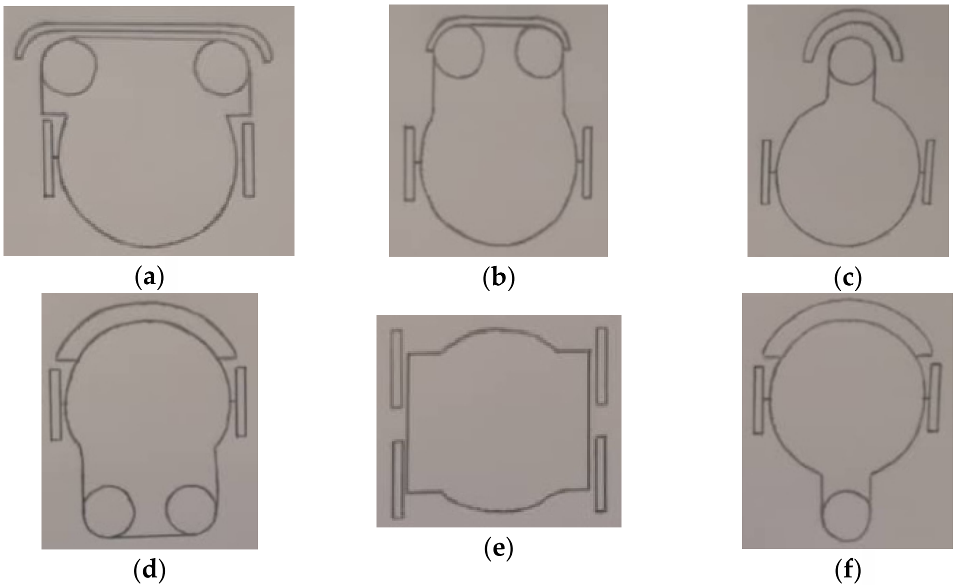


Figure 1. Possible configurations of a smart lawnmower. (**a**) Two-wheel drive with caster wheels at the front. (**b**) Idler wheels mounted before drive wheels and cutting area. (**c**) One wheel instead of two, and the wheel at the front. (**d**) Wheels at the rear. (**e**) Four wheels and no caster wheels. (**f**) Trailing wheel is at the rear.

The design in Figure 1a is one of the most commonly used in commercial smart lawnmowers: a two-wheel drive with caster wheels at the front. The caster wheels protrude from the side of the cutting area to maximise the cutting radius. The castors are at the front to prevent them from being clogged by grass clippings. The design in Figure 1b is a variation of the previous design, with the idler wheels mounted before the drive wheels and cutting area. The final design in Figure 1c uses only one wheel instead of two, and the wheel is at the front of the robot. Having only three wheels ensures that all wheels are in contact with the ground at all times.

Figure 1d shows a design that uses wheels at the rear, while Figure 1e shows a design that uses four wheels and no caster wheels. Not many commercial smart lawnmowers use the four-wheel design because lawns are rarely level (one wheel is often in the air), and costs increase when four engines are used instead of two. In the last design in Figure 1f, the trailing wheel is at the rear end of the robot.

Every design has its advantages and disadvantages. Improvements and changes can be made to any of the existing configurations to improve performance and remove limitations.

1.3.2. Cutting Blade

Unlike conventional lawnmowers, which typically use a thick metal strip that spins and is usually powered by a small internal combustion engine and needs to be reground from time to time, the blades of a smart lawnmower are specially designed and are quite different from those of a conventional lawnmower. The cutting blades can be divided into 2 main categories: fixed or pivoting.

Fixed blades are kept stable by design, such as those from Robomow, which look quite similar to the blades of conventional lawnmowers but are more innovative in terms of design (triangular blades). Due to their size and more robust design, these blades usually need to be replaced less often and are able to cut a wider strip of grass while the mower is moving. The blades can cut closer to the edges of the mower's chassis, making edging more effective. However, the main disadvantages of this type of mower are the higher power consumption, the higher noise level and the risk of damaging objects lying on the lawn, such as small toys.

Pivoting mowers are mowers that have a series of razor blades attached to a spinning disc, usually made of plastic to reduce weight. Therefore, these types of smart mowers are very effective and use little energy. The disadvantage of this system is that the blades are mounted quite far underneath the device, making it very difficult for the mower to mow right up to the edge of a lawn. The razor blades are also delicate and dull more quickly compared to fixed blades, so these blades need to be replaced every few months. However, the replacement blades are cheap, and it only takes 2–3 min to change all the blades [19].

Razor blades can also be used to cut grass into small pieces. Since the cuttings can serve as fertiliser and nutrients for the grassland [20,21], there may no longer be a need for a container to store them.

1.3.3. Sensor

A smart lawnmower uses various sensors to map the garden and track its steps. These include sensors for grass height, sensors that detect the boundary wire, ultrasonic sensors to detect obstacles and collision or bumper sensors. Feedback from these sensors enables the smart lawnmower to automatically move around the grassland and decide where to mow next without human intervention.

Grass height sensors improve the cutting efficiency of a smart lawnmower by preventing the same area from being mowed more than once. This is achieved by the sensor distinguishing the grass height around the lawnmower and determining the direction of travel based on the collected data or signals. Some smart lawnmowers have been improved by incorporating global positioning systems (GPS).

Most smart lawnmower models on the market require the user to run an electric cable around the edge of the lawn and around obstacles such as trees and flower beds. The device moves around the lawn until it hits the boundary wire that limits the working area and then changes course until it hits the wire again. This type of smart lawnmower usually works with a "random" mowing algorithm.

Collision sensors are also known as impact sensors or bumper sensors. Collision sensors are used in many other industrial applications to protect the machine itself and objects in the vicinity. Collision sensors are used in smart lawnmowers or other service robots to prevent damage to products, tools and the robot itself. In less complex devices, collision sensors use a simple pressure switch connected to a surface where collisions are likely to occur. These sensors can also use accelerometers that measure changes in gravity, with rapid changes and high force indicating an unexpected collision.

Non-contact ultrasonic sensors are mainly used by smart lawnmowers or other robots for obstacle detection, as such sensors can work efficiently even in harsh environments. Ultrasonic sensors use high-frequency sound waves, which are above the upper limit of human hearing and can travel through different media (affecting the speed of sound), to determine where an object is located relative to the point of the transducer. This enables the robots to avoid collisions with a detected obstacle from a safe distance [14].

1.4. TRIZ Application in Design

TRIZ is the original name of "Theoria Resheneyva Isobretatelskehuh Zadach" in Russian. "Theory and Innovative Problem Solving" is the English translation of the term. The TRIZ methodology provides a well-structured and powerful process for inventive problem-solving. The application of TRIZ thinking tools in various industries has successfully replaced the unsystematic trial-and-error and brainstorming methods in the search for solutions in the daily lives of engineers and developers. This tool follows a systematic process that is highly reliable, predictable and repeatable. TRIZ is used in many fields, including engineering and business [22].

In engineering design, TRIZ provides a structured method to guide a designer or engineer towards systematic innovation. TRIZ's law of idealism encourages and assists the designer in designing the system ideally, as the TRIZ method has unique ways to effectively determine root causes through the use of the cause-effect chain (CEC). In addition, the concept of contradiction gives the designer the opportunity to focus on his or her ideas. A well-developed technical contradiction can lead the designer to a set of useful, inventive principles using the TRIZ contradiction matrix. Having 40 inventive principles helps the designer overcome psychological inertia [23].

2. Methodology

This study aims to conceptually design a smart lawnmower using the TRIZ approach. This study is an expansion of a prior study's conventional conceptual synthesis [11]. The subsequent research questions (RQs) are formulated in order to fulfil this aim.

RQ1: How can the limitations of a smart lawnmower be resolved using the TRIZ approach?

RQ2: How can TRIZ be integrated into the conceptual design process of a smart lawnmower?

The sequence of the conceptual design process of a TRIZ-integrated smart lawnmower is as follows:

- Step 1: TRIZ analysis of the main problem;
    - i. Cause-effect chain analysis;
    - ii. Technical contradiction;
    - iii. Physical contradiction;
    - iv. Substance field analysis;
- Step 2: Scoring of proposed solutions;
- Step 3: Combining selected solutions with the base model of the smart lawnmower;
- Step 4: Final concept generation;
- Step 5: Design and analysis.

In this study, TRIZ analysis (Step 1) is first applied to each of the constraints listed in Table 1. The constraints suggest the following: (1) the lawnmower cannot be moved smoothly on uneven grassland or high grass, (2) the lawnmower needs frequent recharging, and (3) the products are difficult to obtain in the local Malaysian market.

Table 1. List of identified constraints of autonomous robotic lawnmowers.

No.	Constraints
1	Cannot move smoothly on uneven grassland or ground with tall grass
2	Needs to be recharged frequently
3	Availability in the local Malaysian market is estimated to be low

Step 2 to step 5 is the step-by-step conceptual design process to develop a final model of a smart lawnmower with high potential to solve the identified constraints. In step 2, the proposed solutions are assessed for cost-effectiveness, complexity, manufacturability and suitability. This means that each of the solutions proposed by TRIZ is re-evaluated and compared before being adopted. Only the selected key features are then combined with the base model of the smart lawnmower in step 3. The base model is created by comparing different smart lawnmowers on the market, including Robomow RC 308u Pro, Honda Miimo 40 Live, Bosch Indego M+ 700 and Gardena Smart Sileno+. The selection of materials is also part of this step. Once the smart lawnmower design is completed, it is illustrated by hand sketches with labels in step 4. In the last step, the hand sketches are converted into a computer-aided drawing (CAD) so that they can be provided with a structural analysis. The structural analysis helps validate and optimise the design.

3. Results

3.1. RQ1: Resolving Limitations of a Smart Lawnmower Using the TRIZ Approach

Step 1: TRIZ Analysis of the Main Problem

According to RQ1 (How can the limitations of a smart lawnmower be resolved using the TRIZ approach?), the constraints can be solved using CEC analysis, technical contradictions, physical contradictions and substance field (Su-field) analysis.

Resolving Constraint 1: Figure 2 shows the CEC analysis for constraint 1. There are a total of 2 causes for constraint 1, namely: (a) the power or torque of the mower is insufficient, and (b) the chosen mode of locomotion is not suitable for the design. For each cause mentioned, an obvious solution is proposed. A step-by-step application of the TRIZ analysis tools for the identified constraint follows:

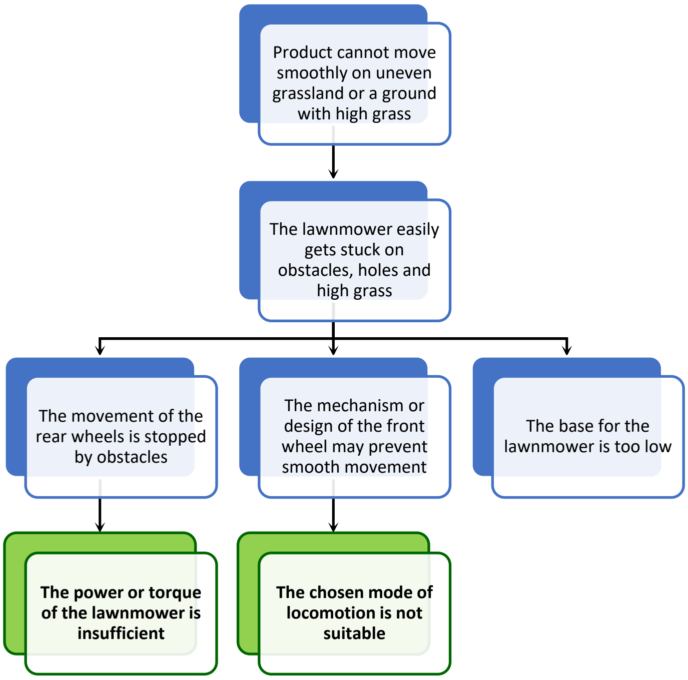


Figure 2. CEC analysis for constraint 1.

Constraint 1: Cannot move smoothly on uneven grassland or ground with tall grass.

(a) Use motors with higher power or torque.
- Use periodic actions and also increase the power if necessary.
- Use other types of power supply (solar energy).

(b) Use other types of locomotion.
- Gliding locomotion.

(c) Centre pivot.
(d) Larger rear wheels.

Technical Contradiction (TC) and TRIZ Contradiction Matrix for Constraint 1: Inventive problems are written in terms of "if-then-but". Since this constraint has 2 main causes, there are also 2 sets of technical contradictions. The parameters in both sets of technical contradictions have been identified, as shown in Table 2.

Table 2. System parameters for technical contradictions (constraint 1).

TC	Manipulative Variable	Responding Variables	System Parameters
1	If motors with higher power or torque are used	Improving: Then the movement of the mower will be smoother	#35 Adaptability
		Worsening: However, more energy will be consumed	#19 Energy spent by a moving object
2	If another type of locomotion is used	Improving: Then the movement of the lawnmower will be smoother	#35 Adaptability
		Worsening: However, the complexity of the design increases	#36 Complexity of device

TC1: If motors with higher power or torque are used, then the movement of the mower will be smoother (#35, adaptability), but more energy will be consumed (#19, energy spent by a moving object).

TC2: If another type of locomotion is used, then the movement of the lawnmower will be smoother (#35, adaptability), but the complexity of the design increases (#36, complexity of the device).

The inventive principles are also identified using the Altshuller or contradiction matrix, as shown in Table 3. By intersecting the improving and worsening parameters, a list of inventive principles can be extracted from the matrix.

Table 3. Inventive principles from system parameters of technical contradictions (constraint 1).

Technical Contradiction (TC)	Pairs of System Parameters	Inventive Principles
TC1: If motors with higher power or torque are used, then the movement of the mower will be smoother, but more energy will be consumed	#35 Adaptability (improving) #19 Energy spent by a moving object (worsening)	#19 Periodic action #35 Parameter changes #29 Pneumatic and hydraulic #13 The other way around
TC2: If another type of locomotion is used, then the movement of the lawnmower will be smoother, but the complexity of the design increases	#35 Adaptability (improving) #36 Complexity of device (worsening)	#15 Dynamisation #29 Pneumatic and hydraulic #37 Thermal expansion #28 Mechanical substitution

Table 4 shows the proposed solutions based on the inventive principles obtained from the intersection of parameters #35, adaptability, and #19, energy spent by a moving object within the contradiction matrix. The proposed solutions are based on the guidelines or rules of the inventive principles.

Table 4. Proposed solutions based on principles from parameters #35 and #19 within the contradiction matrix.

Inventive Principles	Proposed Solutions
i. Periodic Action (#19)	N/A
ii. Parameter Changes (#35)	Utilise a different type of energy supply other than the battery.
iii. Pneumatic and Hydraulic (#29)	Adjustable wheel height through pneumatic or hydraulic control.
iv. The other way around (#13)	Swap front and rear wheels.

Table 5 shows the proposed solutions based on the inventive principles resulting from the intersection of parameters #35, adaptability and #36, complexity of the device, within the contradiction matrix.

Table 5. Proposed solutions based on principles from parameters #35 and #36 within the contradiction matrix.

Inventive Principles	Proposed Solutions
i. Dynamization (#15)	Use track belt or slip locomotion.
ii. Pneumatic and Hydraulic (#29)	Adjustable wheel height through pneumatic or hydraulic control.
iii. Thermal Expansion (#37)	N/A
iv. Mechanical Substitution (#28)	N/A

Physical Contradiction (PC) for Constraint 1: In this study, the formulation of the physical contradictions for the two identified root causes involves two justified contradictory (opposing) requirements for one of the parameters of the technical system or its components. The ideas or solutions are proposed based on the inventive principles for separation in space and time, whichever applies. The strategy of separation in time is not applicable. Therefore, only spatial separation is considered.

PC1: The power or torque of the motor must be high to ensure smooth movement (+a), and the power or torque must be low to save energy (−a).

i. Space:

(+a): Where does the lawnmower need high-power and high-torque motors? (Answer: on uneven grassland.)

(−a): Where does the lawnmower need low-power, low-torque engines? (Answer: on level grassland.)

ii. Time:

(+a): When does the lawnmower need high-power and high-torque engines? (Answer: during operation).

(−a): When does the lawnmower need low-power, low-torque engines? (Answer: when not in use—not applicable.)

PC2: The other method of locomotion must be used to allow smooth movement (+b), and the original method of locomotion must be used to obtain a simpler design (−b).

i. Space:

(+b): Where does the lawnmower need the other method of locomotion? (Answer: on uneven grassland.)

(−b): Where does the lawnmower need the original kind of locomotion? (Answer: on level grassland.)

ii. Time:

(+b): When does the lawnmower need the other type of locomotion? (Answer: while it is in operation.)

(−b): When does the lawnmower need the original mode of locomotion? (Answer: when not in use—not applicable.)

The inventive principles used for the strategy of separation in space are listed in Table 6. Based on the rules of these inventive principles, several proposed solutions can be outlined.

Substance Field (Su-Field) Analysis for Constraint 1: The Su-field model is constructed. The ineffective complete systems are identified, where the standard wheels do not move effectively on uneven grassland because the electric motor does not deliver enough power with the existing specifications (see Figure 3).

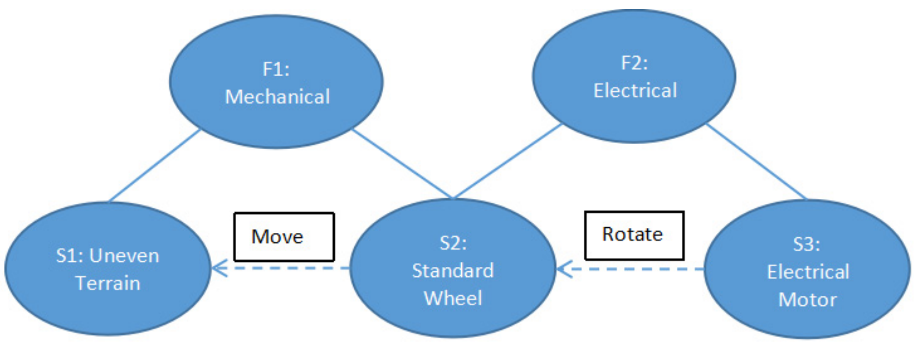


Figure 3. Su-field model for constraint 1.

Table 6. Inventive principles for separation in space and the proposed solutions.

Inventive Principles	Proposed Solutions
(a) Segmentation (#1)	N/A
(b) Taking Out or Extraction (#2)	N/A
(c) Local Quality (#3)	N/A
(d) Another Dimension (#17)	Use bigger wheels
(e) The Other Way Around (#13)	Swap the configuration of the front wheels with the rear wheels
(f) Spheroidality-Curvature (#14)	N/A
(g) Nested Doll (#7)	N/A
(h) Flexible Shells and Thin Films (#30)	Centre pivot design
(i) Asymmetry (#4)	N/A
(j) Intermediary (#24)	N/A
(k) Universality (#6)	N/A

The solution model underlying the incomplete Su-field model involves a change of substance or field. An improved Su-field model is constructed by adding an additional field (solar energy) between S2 and S3 (see Figure 4). The ineffective system is solved by adding solar energy (field) to supply the electric motor with additional energy.

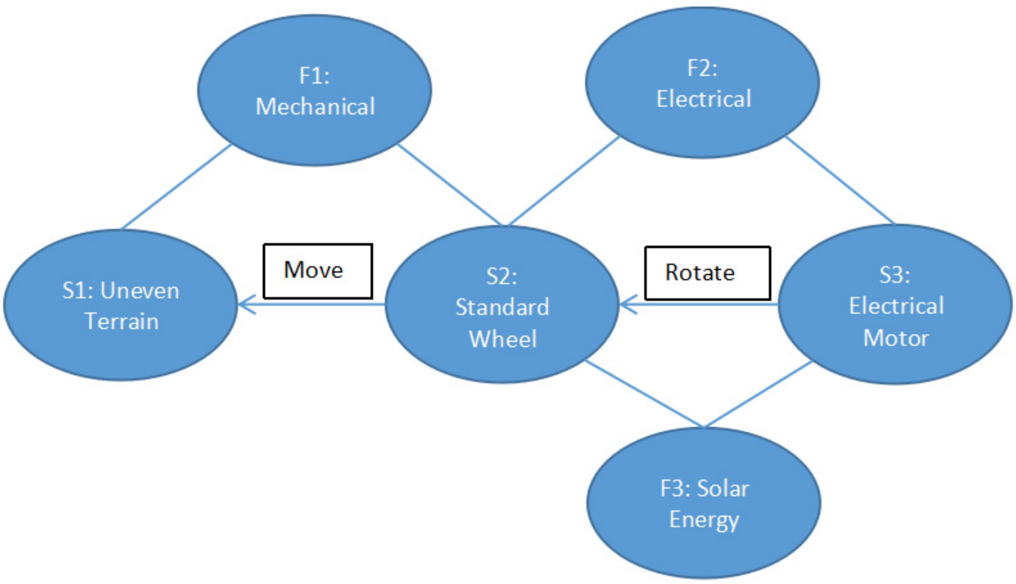


Figure 4. Improved Su-field model for constraint 1.

Resolving Constraint 2: Figure 5 shows the CEC analysis for constraint 2. According to the CEC, the product needs to be recharged frequently because the battery runs out quickly due to its low capacity. For each stated cause, an obvious solution is proposed. A step-by-step application of the TRIZ analysis tools for the identified constraint follows:

Constraint 2: Needs frequent recharging.

(a) Provide holes in the body of the mower wherever possible to reduce weight.
(b) Use a solar charge controller.

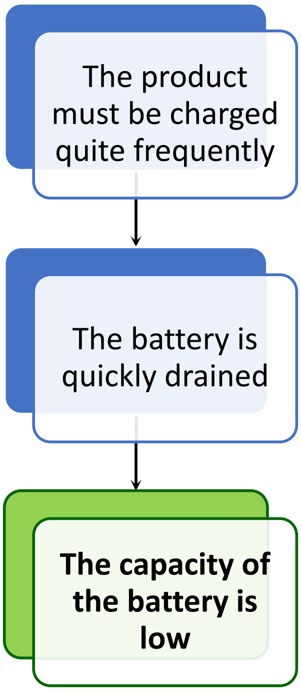


Figure 5. CEC analysis for constraint 2.

Technical Contradiction (TC) and TRIZ Contradiction Matrix for Constraint 2: The technical contradiction follows the same if-then-but method as in the previous section. The system parameters associated with the technical contradiction are listed in Table 7, and the inventive principles resulting from the intersection of the selected system parameters in the contradiction matrix are listed in Table 8. The statement of the contradiction is proposed as follows:

Table 7. System parameters for technical contradictions (constraint 2).

Manipulative Variable	Responding Variables	System Parameters
If a battery with a higher capacity (or more batteries) is used	Improving: Then the lawnmower can work longer	#19 Use of energy by the moving object
	Worsening: However, the weight of the lawnmower is increased as a result	#1 Weight of the moving object

Table 8. Inventive principles from system parameters of technical contradictions (constraint 2).

Technical Contradiction (TC)	Pairs of System Parameters	Inventive Principles
If a battery with a higher capacity (or more batteries) is used, then the lawnmower can work longer, but the weight of the lawnmower is increased as a result	#19 Use of energy by the moving object (improving) #1 Weight of the moving object (worsening)	#12 Equipotentiality #18 Mechanical Vibration #28 Mechanical Substitution/Another Sense #13 Porous Material/Holes

TC: If a battery with a higher capacity (or more batteries) is used, then the lawnmower can work longer (#19, use of energy by the moving object), but the weight of the lawnmower is increased as a result (#1, weight of the moving object).

Table 9 shows the proposed solutions based on the inventive principles resulting from the intersection of parameters #19, use of energy by the moving object, and #1, weight of the moving object within the contradiction matrix.

Table 9. Proposed solutions based on principles from of parameters #19 and #1 within the contradiction matrix.

Inventive Principles		Proposed Solutions
(a)	Equipotentiality (#12)	Use track belt or slip locomotion.
(b)	Mechanical Vibration (#18)	Adjustable wheel height through pneumatic or hydraulic control.
(c)	Mechanical Substitution/Another Sense (#28)	N/A
(d)	Porous Material/Holes (#13)	N/A

Physical Contradiction (PC) for Constraint 2: The physical contradiction formulated for constraint 2 follows the same process as in the previous section. The ideas or solutions are proposed based on the inventive principles for separation in space, time, and conditions, whichever is applicable. The two strategies of separation in space and time are not applicable. Therefore, only the strategy of separation by conditions is considered.

PC: The capacity of the battery must be high to increase the working time (+a), and the capacity of the battery must be low to reduce product weight (−a).

i. Place:

(+a): Where does the lawnmower need the high-capacity battery? (Answer: on the grassland.)

(−a): Where does the lawnmower need the low-capacity battery? (Answer: not on the grassland—not applicable.)

ii. Time:

(+a): When does the lawnmower need the high-capacity battery? (Answer: while it is in operation.)

(−a): When does the lawnmower need the low-capacity battery? (Answer: when it is not in operation—not applicable.)

iii. Condition:

(+a): The lawnmower needs a higher-capacity battery when it has to work for a longer period of time.

(+a): The lawnmower requires a lower-capacity battery when it does not need to operate for a prolonged period of time.

The inventive principles used for the strategy of separation by conditions are listed in Table 10. Based on the rules of these inventive principles, several proposed solutions can be outlined.

Table 10. Inventive principles for separation by condition and the proposed solutions.

Inventive Principles		Proposed Solutions
(a)	Parameter Changes (#35)	N/A
(b)	Colour Changes (#32)	N/A
(c)	Phase Transition (#36)	N/A
(d)	Porous Material/Holes (#31)	Intentionally make holes wherever possible to reduce weight (optimisation)
(e)	Strong Oxidants/Enriched Atmosphere (#38)	N/A
(f)	Inert Atmosphere/Calmed Atmosphere (#39)	N/A
(g)	Mechanics Substitution/Another Sense (#28)	Use solar charging
(h)	Pneumatic and Hydraulics/Fluidity (#29)	N/A

Substance Field (Su-Field) Analysis for Constraint 2: Similar to the previous section, a Su-field model is constructed. The ineffective overall system is identified, where the battery is not effectively charged by the electric power supply (see Figure 6).

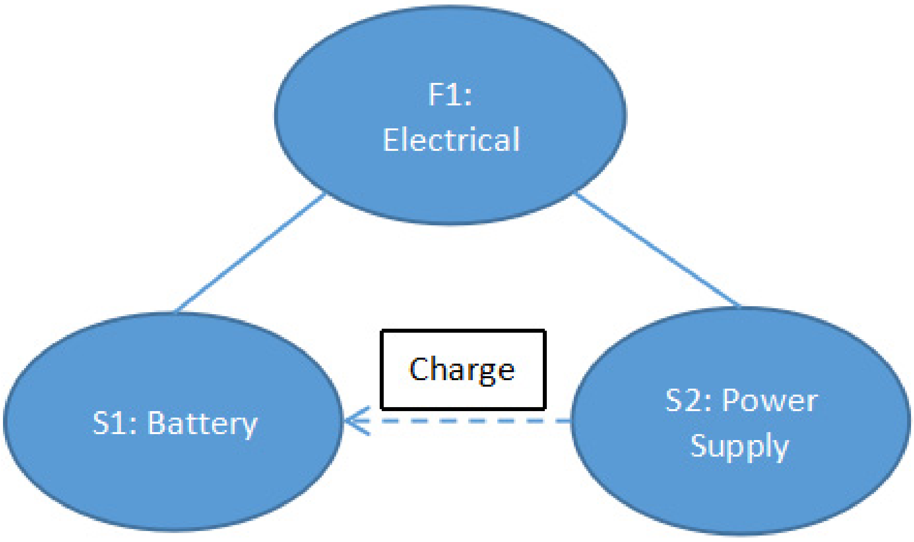


Figure 6. Su-field model for constraint 2.

The improved Su-field model involves a change of substance. The ineffective system is essentially solved by adding a solar panel (substance) to the model (See Figure 7). This allows the lawnmower to be charged while mowing under the sun, which increases the mowing time.

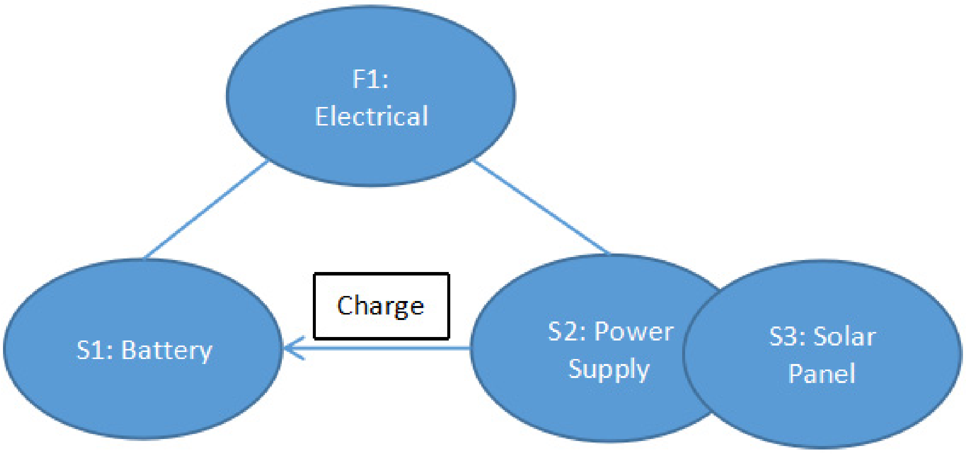


Figure 7. Improved Su-field model for constraint 2.

Resolving Constraint 3: Figure 8 shows the CEC analysis for constraint 3. Based on the CEC, the availability of the product in the local Malaysian market is estimated to be low because the product is costly due to its expensive components or parts, which is due to the lack of new or advanced technologies in robotic mowers. Some possible solutions that are obvious to designers can be suggested as follows:

Constraint 3: Availability in the local Malaysian market is considered to be low.

(a) Use other materials or technologies to minimise cost.
(b) Use a modular design concept to reduce maintenance costs.

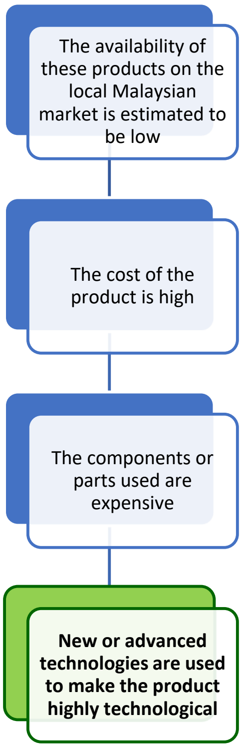


Figure 8. CEC analysis for constraint 3.

Technical Contradiction (TC) and TRIZ Contradiction Matrix for Constraint 3: The technical contradiction follows the same if-then-but method as in the previous section. The system parameters associated with the technical contradiction are listed in Table 11, and the inventive principles resulting from the intersection of the selected system parameters in the contradiction matrix are listed in Table 12. The statement of the contradiction is proposed as follows:

Table 11. System parameters for technical contradiction (constraint 3).

Manipulative Variable	Responding Variables	System Parameters
If new or advanced technologies are used	Improving: Then the lawnmower can perform better	#27 Reliability
	Worsening: However, the complexity of the lawnmower is increased	#36 Device complexity

Table 12. Inventive principles from system parameters of technical contradictions (constraint 3).

Technical Contradiction (TC)	Pairs of System Parameters	Inventive Principles
If new or advanced technologies are used, then the lawnmower can perform better, but the complexity of the lawnmower is increased	#27 Reliability (improving) #36 Device complexity (worsening)	#13 The other way around #35 Parameter changes #1 Segmentation

TC: If new or advanced technologies are used, then the lawnmower can perform better (#27, reliability), but the complexity of the lawnmower is increased (#36, device complexity).

Table 13 shows the proposed solutions based on the inventive principles resulting from the intersection of parameters #27, reliability, and #36, device complexity, within the contradiction matrix.

Table 13. Proposed solutions based on principles from of parameters #27 and #36 within the contradiction matrix.

Inventive Principles	Proposed Solutions
(a) The Other Way Around (#13)	Use other materials or technologies to minimise costs
(b) Parameter Changes (#35)	N/A
(c) Segmentation (#1)	Use the modular design concept to reduce maintenance costs

Physical Contradiction (PC) for Constraint 3: The physical contradiction proposed for constraint 3 follows the same procedure used in the previous section. The solutions are proposed according to the inventive principles for separation in space, time, and conditions. However, the two strategies of separation in space and time are not applicable. Therefore, the strategy of separation by conditions is considered.

PC: The technologies used must be more advanced to improve product performance (+a) and the technologies used must be less advanced to reduce product complexity (−a).

i. Space:

(+a): Where does the lawnmower need more advanced technologies? (Answer: on the grassland.)

(−a): Where does the lawnmower need less advanced technologies? (Answer: not on the grassland—not applicable.)

ii. Time:

(+a): When does the lawnmower need more advanced technologies? (Answer: while it is in operation.)

(−a): When does the lawnmower need less advanced technologies? (Answer: when it is not in operation—not applicable.)

iii. Condition:

(+a): The lawnmower needs more advanced technologies if it is to perform better.

(−a): The lawnmower needs less advanced technologies if it is to reduce design complexity.

The inventive principles normally used to support the strategy of separation by conditions have already been listed in Table 10. However, the researcher was not able to propose a solution or idea based on any of the principles. Therefore, this tool was eventually not used in resolving constraint 3.

Substance Field (Su-Field) Modelling for Constraint 3: Similar to the previous section, a Su-field model is created. The excessive complete system is identified, where the sophisticated system excessively controls the smart lawnmower (see Figure 9).

The improved Su-field model involves a change of substance. The excessive complete system is basically solved by replacing the advanced system with one that is simple but sufficient to perform the specific tasks of a smart lawnmower (see Figure 10).

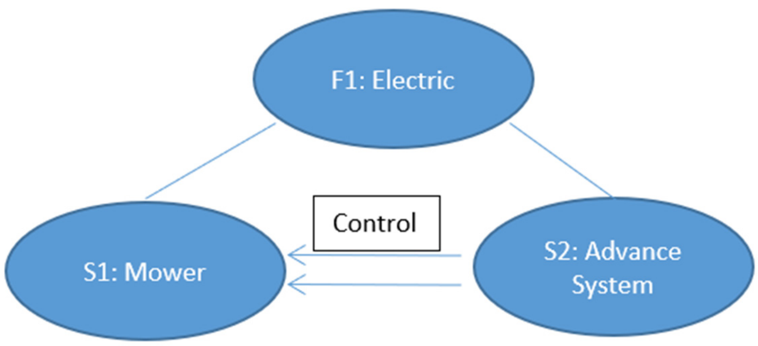


Figure 9. Su-field model for constraint 3.

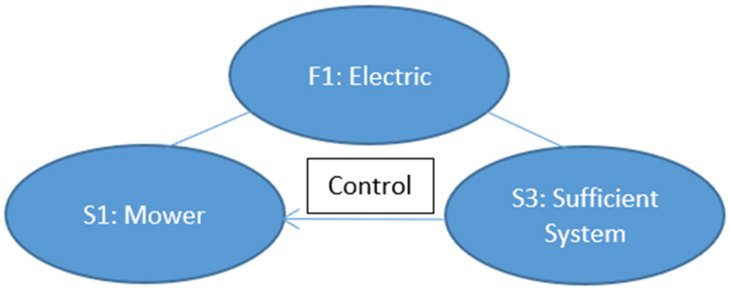


Figure 10. Improved Su-field model for constraint 3.

3.2. RQ2: TRIZ-Integrated Conceptual Design Process of a Smart Lawnmower

3.2.1. Step 2: Scoring of Propose Solutions

Based on the TRIZ analysis, there are a total of 8 different proposed solutions that have the potential to solve the three constraints of the smart lawnmower listed in Table 14. In order to determine the applicability and functionality of the proposed solutions, a scoring process is carried out for the proposed solutions.

Table 14. List of proposed solutions from TRIZ methodology.

No.	Limitation	Proposed Solution	Advantages	Disadvantages
1	Unable to move smoothly on uneven grassland or ground with tall grass.	1. Use motors with higher power or torque.	High effectiveness with minimal modification.	Higher energy consumption.
		2. Use a different method of locomotion.	Can handle most types of grasses.	Difficulties in production.
		3. Use larger wheels.	Simpler in design.	Low effectiveness.
		4. Use a pivot design.	Can adapt to uneven grassland.	Complicated design.
2	Must be charged quite frequently.	5. Deliberately make holes in the body of the lawnmower wherever possible to reduce weight.	With minimal and simple change.	May affect performance in terms of water resistance or waterproofing.
		6. Use the possibility of solar charging.	Use of renewable energies.	Higher cost.
3	The availability of these products in local Malaysian markets is considered low.	7. Use other materials or technologies to minimise costs.	Reduce costs and complexity.	May reduce working efficiency and overall performance of the mower.
		8. Use the modular design concept to reduce maintenance costs.	Reduce maintenance costs and improve design sustainability.	More parts need to be assembled.

The scoring process for the listed proposed solutions is shown in Table 15. There are 4 selection criteria used to evaluate each key feature: cost, simplicity, feasibility and suitability. Only key features with a score above the set threshold are selected. After the scoring process, the proposed solutions with a total score of less than 3 were neglected. Table 16 shows the 7 proposed solutions with a score of 3 or more. The scoring system used for the scoring process ranged from 1 to 5, and the description for each score was defined as follows:

- Score 1: much worse than expected;
- Score 2: worse than expected;
- Score 3: met expectations;

- Score 4: exceeded expectations;
- Score 5: greatly exceeded expectations.

Table 15. Suggested solutions and evaluations.

Key Features		Selection Criteria				Total Score	Rank	Continue?
		Cost (30%)	Simplicity (20%)	Feasibility (30%)	Suitability (20%)			
1	Rating	3	4	5	4	4.0	1	Yes
	Weighted Score	0.9	0.8	1.5	0.8			
2	Rating	1	1	2	3	1.7	5	No
	Weighted Score	0.3	0.2	0.6	0.6			
3	Rating	2	2	5	4	3.3	3	Yes
	Weighted Score	0.6	0.4	1.5	0.8			
4	Rating	4	2	2	4	3.0	4	Yes
	Weighted Score	1.2	0.4	0.6	0.8			
5	Rating	4	4	4	1	3.4	2	Yes
	Weighted Score	1.2	0.8	1.2	0.2			
6	Rating	2	2	4	4	3.0	4	Yes
	Weighted Score	0.6	0.4	1.2	0.8			
7	Rating	2	2	4	4	3.0	4	Yes
	Weighted Score	0.6	0.4	1.2	0.8			
8	Rating	4	2	2	4	3.0	4	Yes
	Weighted Score	1.2	0.4	0.6	0.8			

Table 16. List of the selected proposed solutions.

Constraint	Selected Lawnmower Features
Unable to move smoothly on uneven grassland or ground with tall grass.	Use motors with higher power or torque
	Use larger wheels.
	Use a pivot design.
Must be charged quite frequently.	Deliberately make holes in the body of the lawnmower wherever possible to reduce weight.
	Use the possibility of solar charging.
The availability of these products in local Malaysian markets is considered low.	Use other materials or technologies to minimise costs.
	Use the modular design concept to reduce maintenance costs.

For each constraint, there is more than one proposed solution. This helps to solve the constraints more thoroughly. To enable the smart lawnmower to move smoothly on uneven grassland, the lawnmower is equipped with a pivot point and larger wheels driven by motors with higher power and torque. To reduce the charging time of the smart lawnmower, the power consumption of the smart lawnmower will be reduced by reducing the weight of the lawnmower through a porous housing design and simultaneously charging the lawnmower while it is working using solar cells. Finally, the proposed solutions, such as minimising product costs and reducing maintenance costs, are expected to improve the availability of smart lawnmowers in the Malaysian market.

3.2.2. Step 3: Combining Selected Solutions with Base Model of Smart Lawnmower

The basic model of a smart lawnmower was created by comparing it with some of the smart lawnmowers on the market, namely the Robomow RC 308U Pro, Honda Miimo 40 Live, Bosch Indego M + 700 and Gardena Smart Sileno+. Table 17 shows a comparison of the basic functions of the robotic lawnmowers mentioned.

Table 17. Comparison of the basic features of existing robotic lawnmowers.

No.	Product	Features
1	Robomow RC 308U Pro [24]	i. Mowing width: 28 cm; ii. Mowing height: 16–60 mm; iii. Dimensions: 63 × 46 × 21 cm; iv. Battery type: 26 V lithium; v. Blade type: 1-piece triangular blade; vi. Material: plastic; vii. Locomotion: 2 driving wheels and a front wheel; viii. Navigation system: perimeter wire, collision sensor.
2	Honda Miimo 40 Live [25]	i. Moving width: 19 cm; ii. Mowing height: 30–50 mm; iii. Dimensions: 445 × 364 × 202 cm; iv. Battery type: 18 V lithium; v. Blade type: 3 pivoting blades; vi. Material: plastic; vii. Locomotion: 2 driving wheels and 2 front wheels; viii. Navigation system: perimeter wire, 360-degree sensors.
3	Bosch Indego M+ 700 [26]	i. Moving width: 19 cm; ii. Mowing height: 30–50 mm; iii. Dimensions: 45 × 36 × 20 cm; iv. Battery type: 18 V lithium; v. Blade type: 3 pivoting blades; vi. Material: plastic; vii. Locomotion: 2 driving wheels and 2 front wheels; viii. Navigation system: perimeter wire, intelligent navigation system ("LogiCut"), start-up sensors.
4	Gardena Smart Sileno+ [27]	i. Moving width: 22 cm; ii. Mowing height: 20–60 mm; iii. Dimensions: 44 × 36 × 20 cm; iv. Battery type: 18 V lithium; v. Blade type: 3 pivoting blades; vi. Material: plastic; vii. Locomotion: 2 driving wheels and 2 front wheels; viii. Navigation system: perimeter wire, smart sensor control.

The final decision for each of the basic model characteristics is shown in Table 18. For the dimension-related characteristics such as length, width, height and mowing width of the smart lawnmower, the average of the results of the four existing smart lawnmowers was determined. The battery and blade type selected are a lithium battery and 3 pivoting blades, which were determined by comparing with existing products. Finally, the locomotion method consists of 4 equally sized drive wheels and is different from all existing products as the newly proposed method is said to be able to solve constraint number 1.

Table 18. Base model creation.

Product	L × W × H (cm)	Mowing Width (Disc width)	Material Type (Casing)	Battery Type	Blade Type	Configuration
Robomow RC 308U Pro	63 × 46 × 21	28 cm	Plastic	Lithium	1-piece triangular blade	2 driving wheels and a front wheel
Honda Miimo 40 Live	45 × 36 × 20	19 cm	Plastic	Lithium	3 pivoting blades	2 driving wheels and 2 front wheels
Bosch Indego M+ 700	45 × 36 × 20	19 cm	Plastic	Lithium	3 pivoting blades	2 driving wheels and 2 front wheels
Gardena Smart Sileno+	63 × 51 × 25	22 cm	Plastic	Lithium	3 pivoting blades	2 driving wheels and 2 front wheels
Final decision	54 × 42 × 22	22 cm	Plastic	Lithium	3 pivoting blades	4 driving wheels with same size
Method/ Reason	Averaging	Averaging	Selection of common material. However, wood will be used for prototype	Rechargeable, lower self-discharge rate and more stable	Lower maintenance cost	To accommodate proposed solution no. 4 and solve constraint 1

4. Discussion

4.1. Final Concept Generation

The first version of the final concept was created by hand sketching. Sketching the concept is important because it is a key factor in creative expression and a highly effective visual thinking tool for design. The drawings provide a direct visual reference point for refinement and revision.

The drawings include an isometric view and a sub-view of the concept design to provide a comprehensive representation of the smart lawnmower. The drawings show the general appearance and basic functions of the smart lawnmower. Figure 11 shows the hand-sketched drawing of the final concept that has gone through the conceptual design process.

The smart lawnmower is equipped with a 4-wheel drive system. Additionally, it is mainly made of wood to reduce weight and improve efficiency. The top cover of the smart lawnmower has several sloping surfaces to create more space and area for the solar panels. The solar panels can capture sunlight from different angles to improve the efficiency of the solar charging system. Ultrasonic sensors are used to detect and avoid large obstacles from a certain distance, while bumper sensors protect the mower itself or the object it comes into contact with in the event of a collision. The outer appearance of the smart lawnmower is symmetrical to the front and right planes. The two separate bodies of the lawnmower are fixed from side to side by a central axis of rotation. The central pivot axis allows the two separate bodies to rotate relative to each other and improves flexibility when moving on uneven grassland.

4.2. Design and Analysis

Expectation of current design compared to previous design: An earlier robotic lawnmower made by the authors was able to reduce the height of the grass from 6.84 cm to about 3.36 cm [11]. The present smart lawnmower is designed to mimic the cutting performance of the previous lawnmower as much as possible, i.e., to cut grass with a maximum height of about 7 cm. The operating time of the previous design was also 2.18 h without solar power and 3.21 h with solar power. With the increased area for solar panels, the current smart lawnmower should increase its operating time with solar power. However, due to the larger number of components and materials (wheels, dimensions of the wood, number of solar panels, etc.), the current smart lawnmower has to weigh about 20 kg, which is significantly heavier than the previous prototype (about 8 kg).

Design drawing: With all the design details of the smart lawnmower finalised, such as key features, dimensions and material, the hand sketch can be converted into a computer-aided drawing (CAD) using Autodesk Inventor (version 2019). Table 19 shows the isometric view and the sub-view of the shell and assembly drawings of the smart lawnmower.

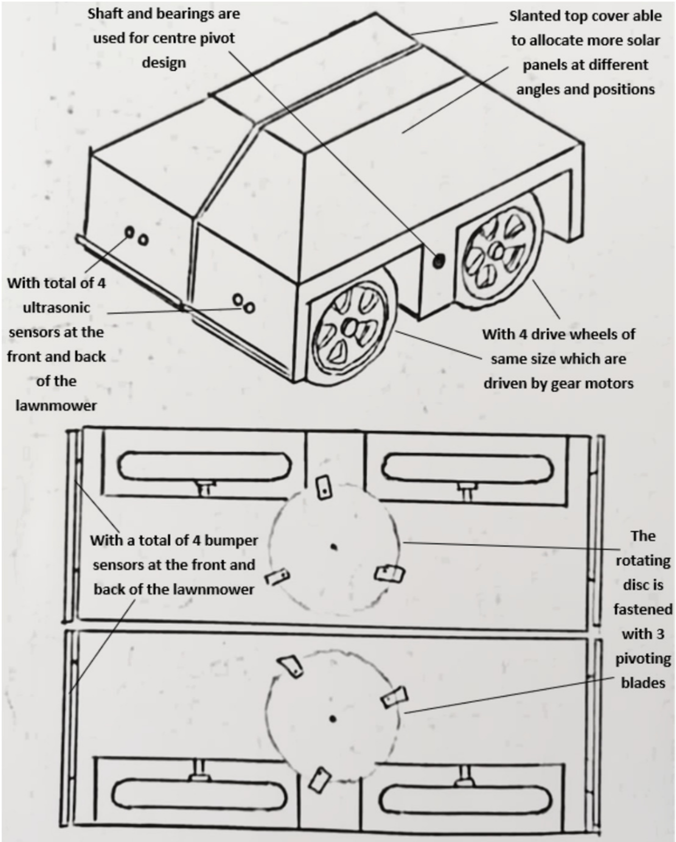
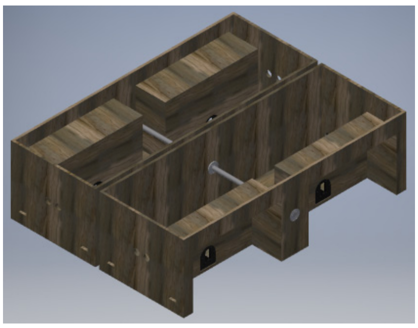
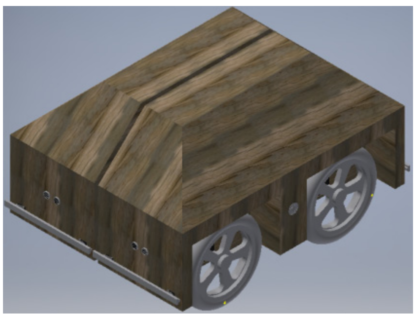
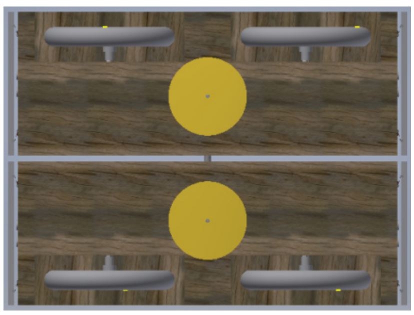


Figure 11. Hand-sketched drawing of the final concept.

Table 19. Isometric and bottom view of the lawnmower (shell and assembly).

Drawing	Isometric View	Bottom View
Shell		
Assembly		

Stress analysis: For the stress analysis, the reaction force on each wheel must be determined using static force analysis. The total weight *W* of the lawnmower is estimated to be 200 N. Since the structure of the smart lawnmower is symmetrical in 2 axes (axis *x* and axis *y*), the reaction force can be calculated by dividing the total weight of the lawnmower by 4, which corresponds to 50 N. The free-body diagram of the lawnmower is shown in Figure 12.

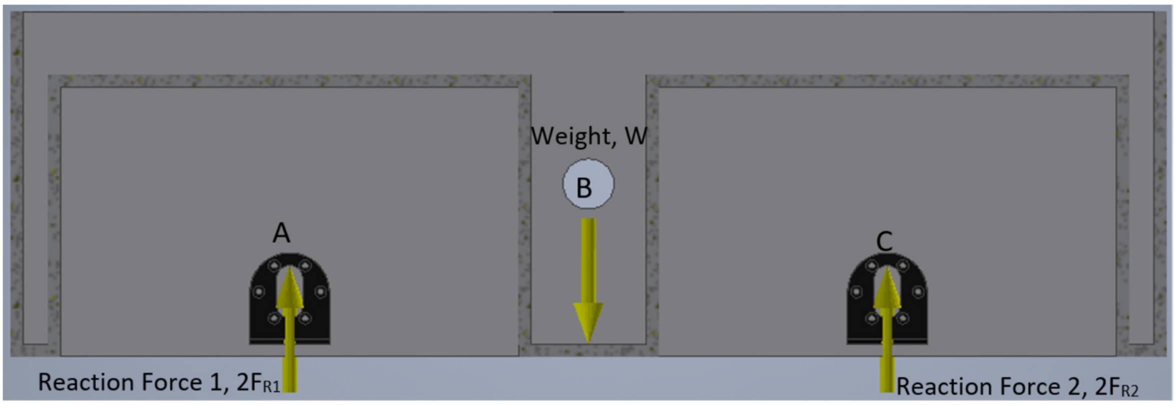
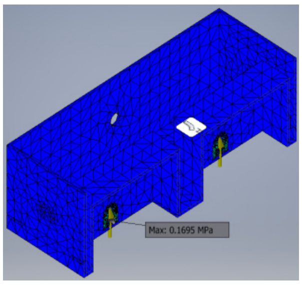
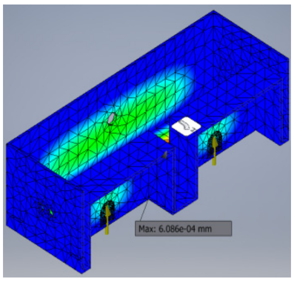
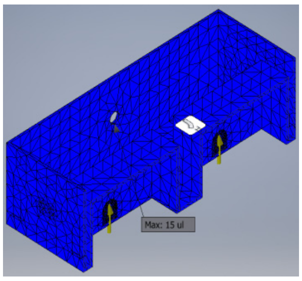


Figure 12. Free-body diagram of the lawnmower. Note: $F_{R1} = F_{R2}$.

Following the material selection in the previous study [11], plywood was used as the material for the lawnmower cover. Table 20 shows the simulation results for the von Mises stress, displacement, and safety factor. The maximum stress (0.1695 MPa) occurs at the attachment of the wheels. On the other hand, the maximum displacement (0.0006086 mm) occurs at the centre of the base, according to the simulation. The minimum safety factor of the lawnmower in the static equilibrium condition is 15, a value higher than 1.

Table 20. Stress simulation results for the prototype (pictures).

Part	Stress Analysis		
	Von Mises Stress (MPa)	**Displacement (mm)**	**Safety Factor**
Casing			

Optimisation of Current Design: After performing the stress analysis, the results show that the safety factor for the stress analysis is significantly higher than 1. This means that the design of the lawnmower is considered an over-engineered design. An over-engineered design is a product that is more robust, unnecessarily complex, inefficient or has more features than are often necessary for its intended use.

For example, based on the load simulation, wasted materials are likely to result in increased weight, cost, and efficiency. To optimise the current design, the dimensions of the design need to be changed (by reducing the thickness), and the stress analysis needs to be repeated to check the safety factor of the design. The results show that the safety factor is still 15, even if the thickness of the plate is reduced to 3 mm. However, further reducing the thickness of the plywood may make woodwork more difficult to produce. Therefore, it is not practical to further optimise the shell design by reducing the thickness of the plywood to less than 3 mm. Table 21 shows the comparison of the stress simulation results before and after optimisation.

Table 21. Comparison of stress simulation results before and after optimisation.

Before Optimisation				After Optimisation			
Thickness (mm)	**Max Stress (MPa)**	**Max Deflection (mm)**	**Safety Factor**	**Thickness (mm)**	**Max Stress (MPa)**	**Max Deflection (mm)**	**Safety Factor**
6	0.1695	0.0006086	15	3	3.536	0.01343	15

5. Conclusions

The constraints of smart lawnmowers include (1) their major limitation: their ability to navigate on uneven grasslands, (2) their first fundamental constraint: the high charging frequency, and (3) their second fundamental constraint: the low availability of a similar product in the Malaysian market. To overcome these constraints, this research aimed to conceptually design a smart lawnmower using the TRIZ approach. In view of this aim, two research questions were formulated: (1) How can the limitations of a smart lawnmower be resolved using the TRIZ approach? and (2) How can TRIZ be integrated into the conceptual design process of a smart lawnmower? The constraints of the smart lawnmower were successfully addressed, and the aim of the study was achieved through a thorough TRIZ-integrated conceptual design process. To answer the first research question, the four main analytical tools of TRIZ, namely cause-effect chain analysis, technical contradiction, physical contradiction and substance field modelling, were applied to each of the constraints of the smart lawnmower. The major limitation of the smart lawnmower has been addressed by increasing the motor power or torque, increasing the wheel diameter and combining it with a central pivot. The first fundamental constraint of the smart lawnmower has been addressed by a solar charging system and keeping the weight of the lawnmower as low as possible. The second fundamental constraint was solved by minimising development and maintenance costs through a modular design.

To address the second research question, a comprehensive conceptual design process for the smart lawnmower was organised to adopt the features suggested by TRIZ and further improve the current smart lawnmower design. The conceptual design process included the evaluation of the features suggested by TRIZ, the creation of a base model by benchmarking existing smart lawnmowers, the selection of materials, concept design, 3D computer-aided design (CAD), design analysis and optimisation.

Future Work

To improve this study, further research can be conducted on relevant products, journals and patents to propose more relevant inventive solutions according to each invention principle for each of the product limitations. The methodology of this study will be further refined, especially in material selection, load simulation and structural analysis. The evaluation of the material selection criteria may change due to changes in design requirements and external influences such as prototyping budgeting. A more thorough finite element analysis (FEA) may need to be performed for the designed structure. The result of the FEA should be verified by various analysis software or theoretical calculations to prove the accuracy of the results.

The development of the prototype can be carried out according to the design plan for testing, inspection and validation of the study. The prototype should be subjected to some functional tests using experimental research paradigms. Depending on the performance during the tests, the prototype may need to be modified and improved. The collected data from each experiment can be used for functional validation and statistical analysis, which may include t-tests, ANOVA and regression.

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