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Research article

Set-based design application on dates harvesting machine

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ABSTRACT

This paper explores the application of Set-based Design (SBD) in the design of a dates harvesting machine. Dates are a popular fruit with significant economic importance, especially in Saudi Arabia. However, the process of harvesting them is highly labour-intensive, and there is a need for an automated solution to improve efficiency and reduce costs. The study begins with a comprehensive review of the literature on other fruit-harvesting machines. The research then proposes an architectural design of a dates harvesting machine based on the understanding of the typical fruit harvesting machines. The dates harvesting machine design proposed in this study consists of several sub-assemblies. Each sub-assembly is designed as a set of alternatives, with different configurations of components, mechanisms and materials. The understanding of the customer requirements of typical date farms helped to identify the list of values that are essential to design the dates harvesting machine. These values were filtered and analysed using an analytical hierarchy process to define three key value attributes of 'design performance', 'safety' and 'cost'. The SBD approach helped to evaluate all the possible combinations of subsystems to identify the optimal solution that meets the customer's requirements and constraints. The SBD methodology resulted in the generation of 576 alternative design configurations which were aggressively narrowed down to 48 design solutions and then into 4 solutions where the final optimized design was selected using the PUGH matrix. The narrowing down is based on the combination of trade-off curves, solution performance and the identified key-value attributes. The proposed dates harvesting machine design shows great promise in improving the efficiency and sustainability of harvesting dates, and it can be adapted for use in agricultural applications.

1. Introduction

The Kingdom of Saudi Arabia is the second-largest producer of dates in the world, with 1.56 million metric tonnes of dates produced in the year 2021 [1]. They continue to harvest these dates by hand, which is a very ineffective, time-consuming, expensive, and hazardous method. The farmers must pay close attention to fruit ripeness conditions throughout the dates harvest season in September of every year and begin harvesting at the appropriate stage. Currently, the entire harvest process is manual, which means every date on

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Table 1
Existing fruits harvesting machine.

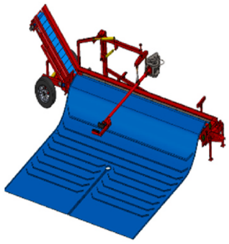
Company	Arusin	Mat-ing	Towering Nuts
Model	Autopick-GTi	Plum and Cherry Harvester	Tornedo
Country	Spain	Serbia	Moldova
Fruits Harvested	Olives, Nuts	Plums, Cherries	Pistachios, Plums, Cherries, Olives, Walnuts
Fruit Collection Mechanism	Umbrella	Rolling Canvas	Manual
Limitations	Maximum diameter of tree trunk that can be harvested 40 cm	More workers required (semi-automatic). Can't reach till high heights.	Maximum diameter of tree trunk that can be harvested 45 cm
Figure			
Source	https://www.arcusin.com/	https://mat-ing.rs/en/	https://toweringnuts.com/

Table 2
SBD applications and practices till year 2020.

Category Publications	1 Industrial Case Study	2 Design Set	3 Supporting SBD	4 SBD as a methodology	5 Reference to SBD
Blindheim et al., 2020 [12]	X				
Ishikawa and Sasaki, 2020 [13]	X				X
Small et al., 2020 [14]		X	X		
Suwanda, Al-Ashaab and Beg, 2020 [15]			X		
Ammar et al., 2019 [16]	X	X		X	
Fitzgerald and Ross, 2019 [17]			X	X	X
Inoue and Suzuki, 2019 [18]	X			X	
Lopes and Zancul, 2019 [19]				X	
Geoffroy et al., 2019 [20]				X	
Schjøtt-Pedersen et al., 2019 [21]	X				
Rempling et al., 2019 [22]			X		X
Saad et al., 2019 [23]	X				X
Wade et al., 2019 [24]		X		X	
Rapp et al., 2018 [25]			X		
Riaz et al., 2017 [26]	X			X	
Landahl et al., 2016 [27]	X	X		X	
Miranda De Souza and Borsato, 2016 [28]			X		
Levandowski, Müller and Isaksson, 2016 [29]					X
Araci, Al-Ashaab and Maksimovic, 2016 [30]			X	X	
Al-Ashaab et al., 2016 [31]	X			X	
Raudberget, Michaelis and Johannesson, 2014 [32]			X	X	X
Levandowski, Michaelis and Johannesson, 2014 [33]			X		X
Ghosh and Seering, 2014 [34]			X	X	
Al-Ashaab et al., 2013 [35]	X	X			
Kerga, Taisch and Terzi, 2013 [36]	X	X	X		
Michaelis, Levandowski and Johannesson, 2013 [37]			X		X
Khan et al., 2011 [38]			X	X	
Raudberget, 2011 [39]	X	X	X		
Avigad and Moshaiov, 2009 [40]			X		X
Parrish et al., 2008 [41]	X			X	
Nahm and Ishikawa, 2006 [42]			X	X	
Sobek, Ward, Liker, 1999 [43]	X			X	
Liker et al., 1996 [44]				X	

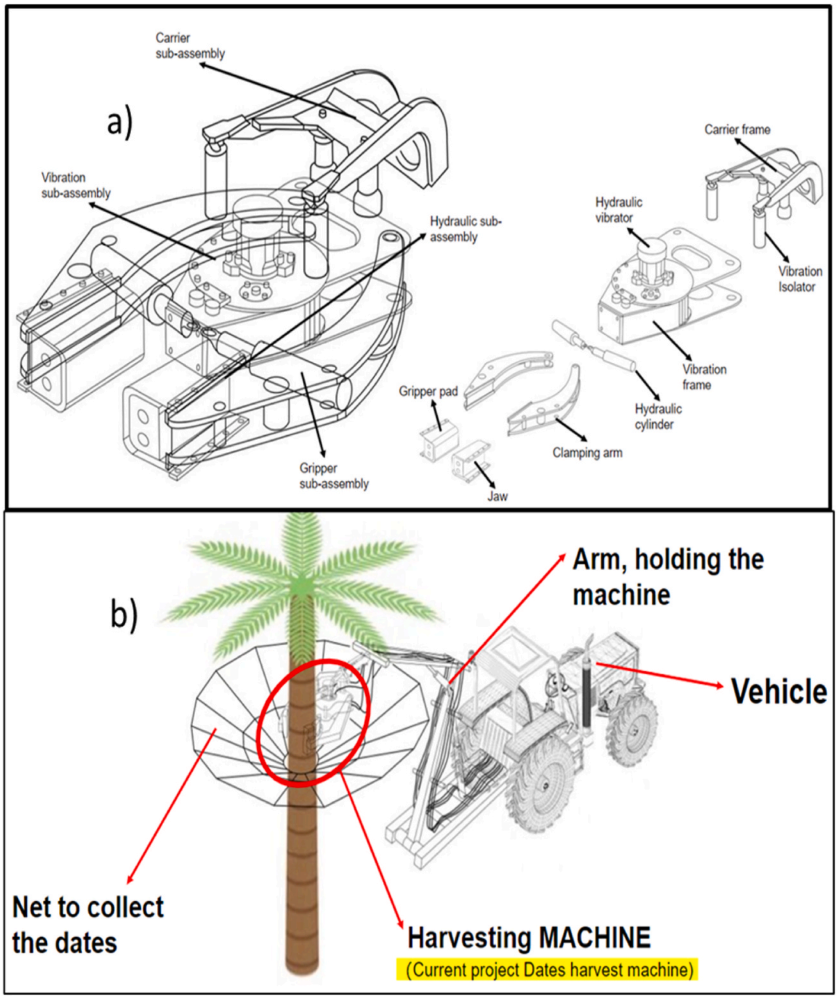


Fig. 1. (a) Architecture of the intended dates harvesting machine (Authors), (b) the full dates harvesting system (Authors).

the farm is collected by farmers by shaking the palm trees to gather the fruit, which then falls into collection nets or bags that have been placed outside of the mature fruit in advance. A worker needs to climb the tree as palm trees are very tall, some dates trees may grow up to 15 m in height. This person cut the dates bunch and throws it to other workers who stand beneath the trunk and manually get the branch of dates. Around 6 to 8 people are working on each palm tree. It takes around 30–45 min to harvest dates in each tree. The number of palm trees in each farm is around 2000 to 25,000 trees that must be harvested within two months of September and October of every year. The current method of harvesting dates is, therefore, labour-intensive and time-consuming for the farm owner, hence the harvesting cost is high, and efficiency is low.

On the other hand, other fruits, such as plums, cherries, and olives, have a considerable degree of automation for harvesting. Commercially, there are several fruits harvesting machines as illustrated in Table 1 with different specifications and features that are suitable for harvesting fruits like Olives, Nuts, and Plums. However, they are not suitable harvesting dates as the palm trees are very tall, the tree trunk diameter is very large compared to other fruits and the tree surface is irregular. Hence, there is a need for a dates harvesting machine with a high level of automation as evident from the reviewed literature there is no machine customized for date harvesting, therefore, the presented solution is a novel design.

This paper seeks to employ the Set-based Design approach, a Lean product development process where sets of solutions are generated concurrently and narrowed down as the design progresses based on the knowledge gained [2], to develop a reliable, innovative, and efficient solution of dates harvesting machine. The guiding principles and ideas of Lean were introduced by Toyota for process improvement [3]. Although Toyota is renowned for its production system, it is widely believed that this is not the only one that is contributing to its success because the Toyota Product Development System also played a significant part in this accomplishment. The literature highlights the significance of set-based concurrent engineering (SBCE), which is interchangeably used with set-based design (SBD) in the context of lean product development (LeanPD) application [4–8]. This is so because the SBD defines the steps that will be taken to produce a product. Value creation, the provision of a "knowledge environment", continuous development, and the SBCE process—all of which promote creativity and teamwork—are its main points of emphasis. LeanPD offers a process model and

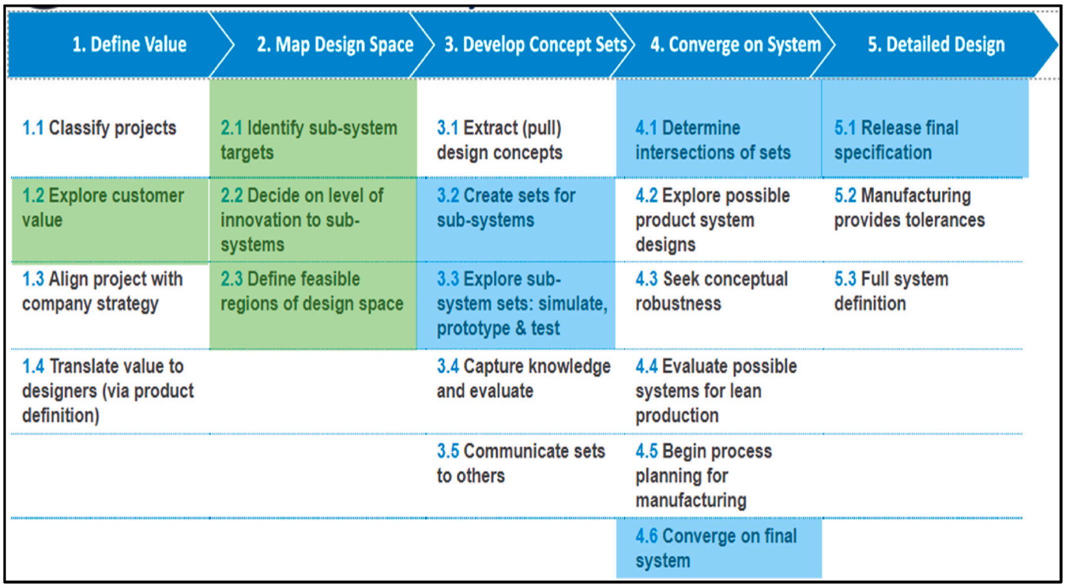


Fig. 2. Set-Based Design Process Model with the highlighted activities indicating the activities performed for designing dates harvesting machine [45].

related resources that consider the full life cycle of a product. To enable value creation for the clients in terms of innovation and customization, quality as well as sustainable and reasonably priced products, it offers knowledge-based user-centric design and a development environment. For this reason, a strong LeanPD should cover the following: 1) Clearly stated lean concepts; 2) Well-defined aspects with at least one development process description; 3) A description of the tools and procedures, 4) Guidelines for implementation, and 5) Case studies that illustrate the methodology. SBCE is defined by Sobek et al. [3] as a simultaneous process of reasoning, developing, and presenting a set of solutions. The set of acquired knowledge is progressively reduced as the design moves forward. According to Morgan et al. [9], SBCE carefully considers all potential options until the maximal "design space" is reached.

The interest in SBD applications has grown during the past few years. Numerous research investigations have been carried out about the application of SBCE in an actual industrial environment. These studies have been arranged and classified in Table 2. The following clarifies each category's meaning.

1) **Industrial case study:** Articles in this category present an industrial case study using set-based design techniques. Much of this research, however, fails to present a coherent SBCE process model or framework.
2) **Design set:** To investigate a set of design solutions, set-based design is used.
3) **Supporting SBCE:** Articles in this category suggest tools and techniques to assist SBCE applications rather than directly implementing SBD (e.g., developing knowledge while exploring the design space [10]).
4) **SBCE as an approach:** Set-based design is not solely used, rather it is used in conjunction with other approaches to product development. Articles in this category make use of alternative methods and tools for product creation.
5) **SBCE Reference:** Although the authors advocate set-based concurrent engineering as a viable technique for product development, it is not adopted (e.g., the collaborator company intends to employ the SBD approach [11])

To find the optimal design solution that satisfies the requirements and constraints of the customer, the SBD technique assisted in evaluating all potential subsystem combinations. 576 potential design configurations were produced by the SBD approach, which was then rigorously reduced to 48 design solutions and finally to 4 solutions, from which the best design was chosen. The combination of trade-off curves, solution performance, satisfaction of the specified key value formed the basis for the narrowing down by the help of methodologies like the analytical hierarchy process and the PUGH matrix. The suggested design for a dates harvesting machine has the potential to significantly increase the sustainability and efficiency of date harvesting, and it can be adapted for usage in actual agricultural settings.

2. Materials and methods

The research methodology consists of four phases. Phase one is about the review of the related literature on set-based design and fruit harvesting machines, this is presented in section one. Phase one resulted in the development of the architecture of the intended dates harvesting machine shown in Fig. 1 and presented in section 2.1. Phase two is the start of the application of the set-based design activities shown in Fig. 2 until the development of the first set of alternative conceptual designs, this is presented in section three. Phase three is the field study in Saudi Arabia visiting five different palm trees farms in the city of Al-Ahsa. This helped in validating the design

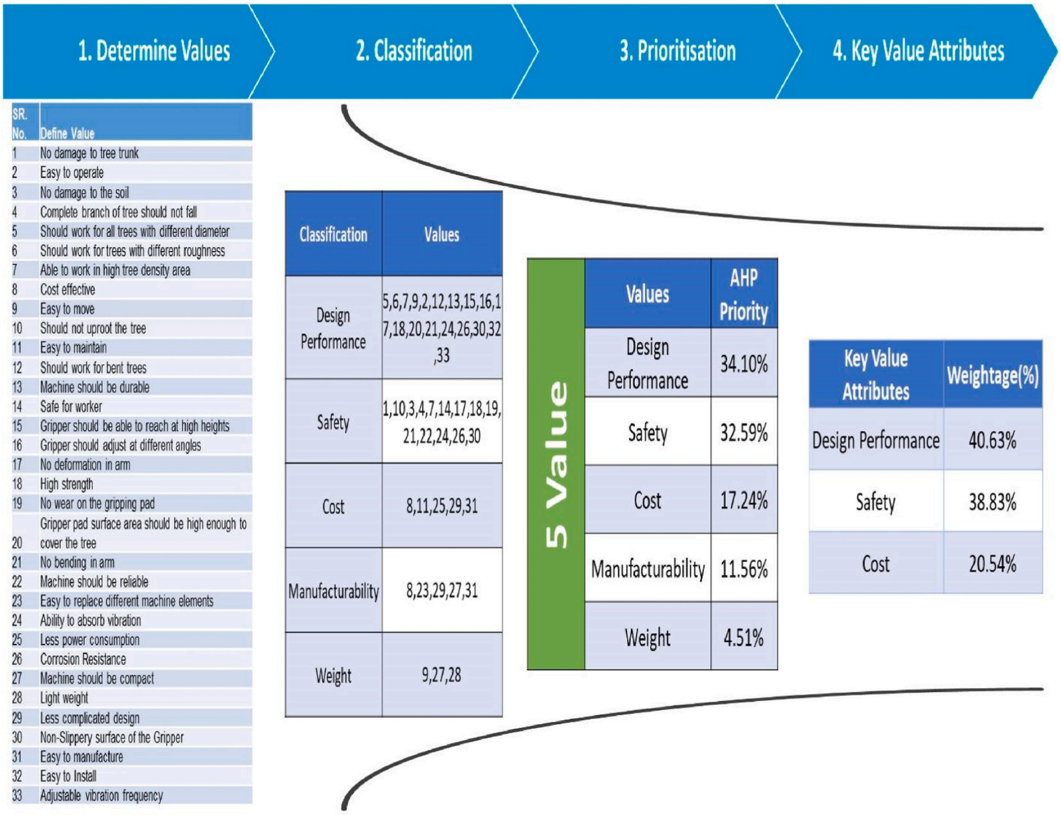


Fig. 3. Explore Customer Values for dates harvesting machine.

parameters with different stakeholders and confirming the right progress of the results of the alternative conceptual design solutions of the application of the set-based design process model. Phase four, which is presented in section four, completed the application of the SBD and converged to the final design solution of the dates harvesting machine.

2.1. The architecture of fruit/dates harvesting machine

The Set-based design process model was implemented to design a “dates harvesting machine”. Fig. 1 illustrates the architecture of the dates harvesting machine and the full dates harvesting system that the authors have made based on the understanding of different fruit harvesting machines. The dates harvesting machine is a machine powered by a mobility vehicle such as a tractor through the hydraulic system, it then clamps the tree trunk firmly, shakes it with a hydraulic vibrator, and collects the dates using a net. The typical sub-assemblies of the intended dates harvesting machine are the following.

1) **Carrier Sub-assembly** – It consists of a carrier frame and vibration isolators. The carrier frame is a supporting frame on which the vibration sub-assembly is suspended through vibration isolators. The vibration isolators reduce the amount of vibration transferring from the hydraulic vibrator to the carrier frame and the back of the machine.
2) **Hydraulic Sub-assembly**- It consists of a hydraulic pump, hydraulic fluid, hydraulic reservoir, hoses, control valve, hydraulic vibrator, and hydraulic cylinder. The hydraulic pump is powered by a mobile vehicle, and it takes hydraulic fluid from a reservoir and pressurises it. The control valve regulates the flow of pressurised fluid which passes through the hoses to the hydraulic vibrator. The hydraulic vibrator extracts energy from pressurised fluid and converts it to mechanical energy and generates necessary vibration.
3) **Vibration Sub-assembly**: It consists of a hydraulic vibrator and vibration frame. The hydraulic vibrator generates the necessary vibration required to harvest the dates. The vibration frame is the main connection between the gripper sub-assembly and carrier sub-assembly. The hydraulic vibrator and hydraulic cylinder are also mounted on this frame.
4) **Gripper Sub-assembly** – It consists of clamping arms, jaws, and gripper pads. The clamping arm moves inward and outward with the help of the hydraulic cylinders attached to it, so it can grip tree trunks with different diameters. Jaws are part of the clamping arm that applies a compressive force on the tree so that the gripper can hold the tree firmly during the shaking of the tree. Gripper pads are attached to the jaws so the machine may not damage the tree, or the jaw may also not get damaged.

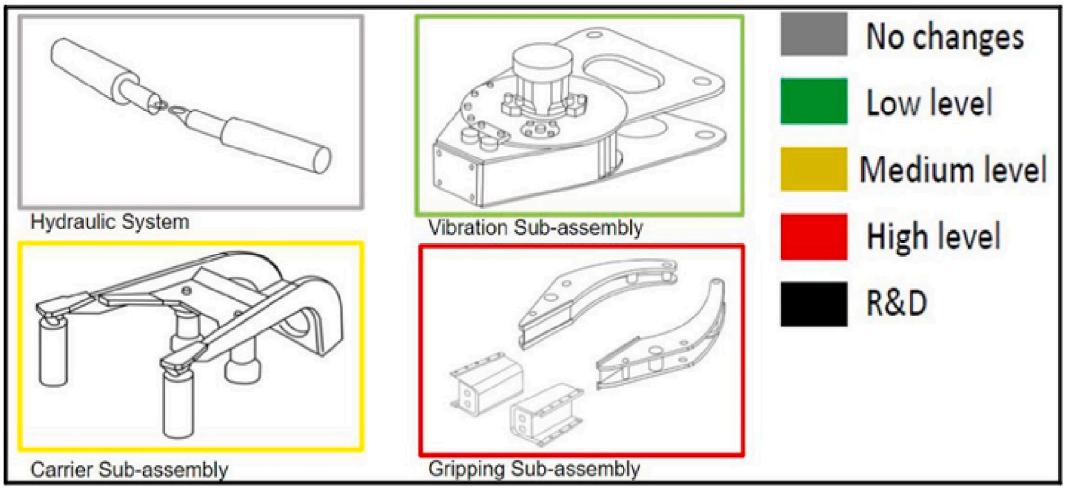


Fig. 4. Level of Innovation for sub-assemblies of dates harvesting machine.

3. Results

The set-based design model is implemented to get to the final design of dates harvesting machine. There are many activities in each phase of set-based design, but not all need to be executed. The activities highlighted in Fig. 2 [45] represent the ones performed by the team to design the machine. The following section presents a detailed application of each activity on the dates harvesting machine.

3.1. Phase 1: Define value

In the phase of "Define Value", the initial concept of the dates harvesting machine is defined based on customer requirements, defining the product value and their targets. It has the following activity:

3.2. Explore customer value

It is important to clearly understand the customer's needs and expectations to design a successful product. Hence, the values were identified through brainstorming and understanding the product's intended application. In this case, an exhaustive list of 33 customer values was generated and illustrated in Fig. 3. These values were further classified into 5 categories based on their similarities in objectives. This categorization helps to ensure that the customer values are accurately understood and can be analysed effectively. For example, the values "No damage to the tree trunk", "Should not uproot the tree" and "No damage to the soil" are all serving the same purpose of "Safety." Similarly, all the values with similar objectives are classified. These 5 customer values are: "Design Performance", "Safety", "Cost", "Weight", and "Manufacturability". Furthermore, each value's importance level had to be assessed and compared with the other values to determine the most important values for designing the machine. The Analytic Hierarchy Process (AHP) matrix was used to achieve this [46,]. It is a decision-making framework used to prioritise multiple complex options (key values as in this case) by arranging them in a hierarchical manner and analyse complex decisions. This is done to identify the loads of importance of each value compared to the other values and if these high prioritised values are taken into considerations, then it will automatically help in generating the final design which meets maximum customer requirements. This led to the generation of key-value attributes (KVA) as shown in Fig. 3 where the 3 highest percentages were selected, which are: 1) Design Performance (34.1%), 2) Safety (32.59%), and 3) Cost (17.24%). This is important because the design cannot satisfy all the values, hence the most relevant values are chosen.

3.3. Phase 2: Map design space

The scope and feasible region of the dates harvesting machine design were identified in the phase of "Map Design Space". It has the following activities:

3.4. Decide on the level of innovation to the sub-system

In this activity, the entire dates harvesting machine was categorised into four different sub-assemblies or sub-systems to analyse each of them individually. The dates harvesting machine consists of; 1) Carrier sub-assembly, 2) Vibration sub-assembly, 3) Hydraulic system, and 4) Gripper sub-assembly. The level of innovation is a colour-coded tool that helps in an easy understanding of the innovation and changes required in each sub-system of a product as shown in Fig. 4.

Table 3
Sub-system targets for dates harvesting machine.

Subsystem	Target
Vibration Sub-assembly	1) Sufficient frequency and amplitude for harvesting dates 2) Should be mounted securely on carrier frame 3) Minimum vibration and shock to machine
Gripping Sub-assembly	1) Sufficient force to grip firmly without damaging tree 2) Sufficient friction on pads for good grip on tree 3) Sufficient clamp opening to cover trees with high diameter 4) Cost effectiveness
Hydraulic System	1) Adequate power to drive all other mechanisms 2) Appropriate flow and pressure of hydraulic fluid 3) Hoses and fittings should provide sufficient pressure and flow capacity 4) Should have a compatible hydraulic fluid
Carrier Sub-assembly	1) Should provide free movement to clamping arm 2) Easy extension up-to the desired tree height 3) Should provide stability and balance to the shaker machine

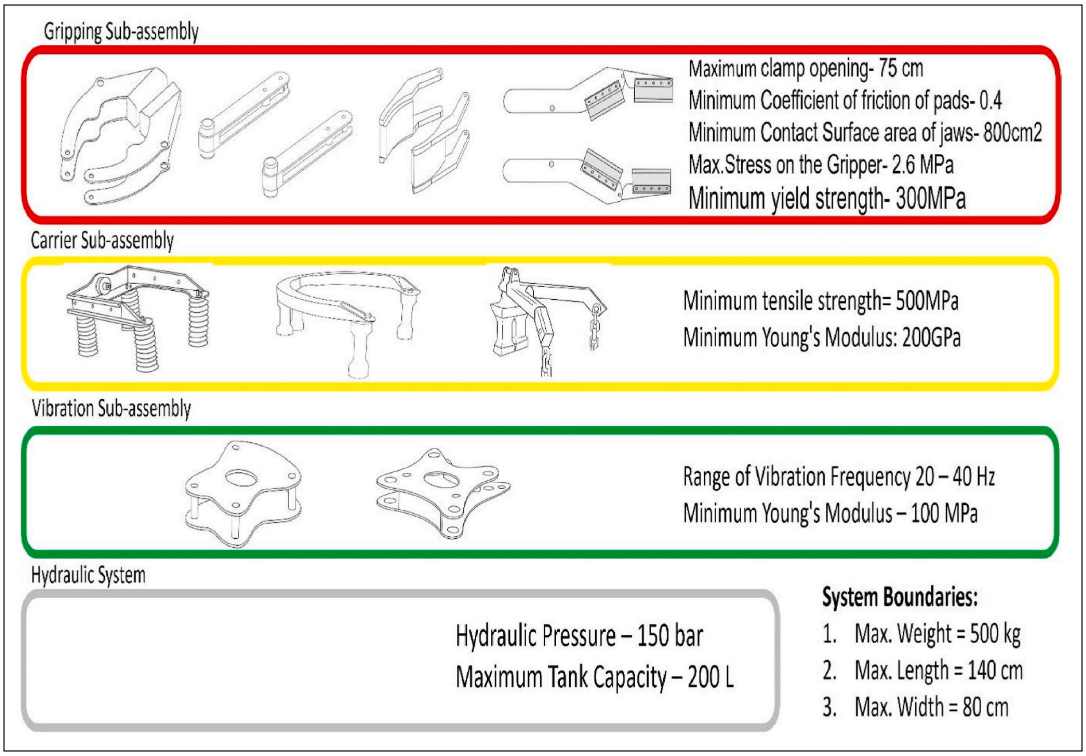
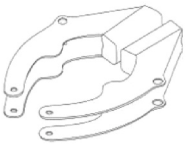
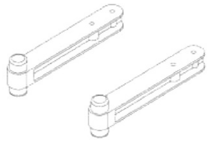
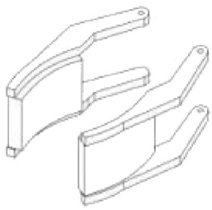
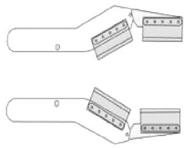
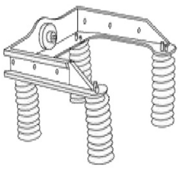
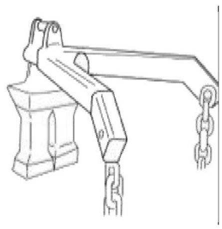
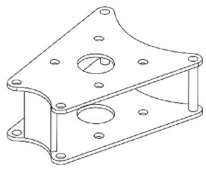
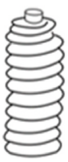


Fig. 5. Design space of the dates harvesting machine.

- **Grey** colour indicates Level 1 innovation, which means no changes are required in this sub-system. In this case, the hydraulic system, mobility vehicle, net to collect the dates are commercially available in the market and just need to be integrated with the designed dates harvesting machine, hence, it requires no change.
- **Green** denotes Level 2 innovation which means low-level innovation. The vibration sub-assembly is coded as green because it requires minute changes to integrate the commercially available vibrator and the gripper in it.
- **Yellow** represents a medium level of innovation, which in this case has been represented by the carrier frame. The carrier frame needs to mount the entire machine hence, it requires some level of innovation. Also, the commercially available vibration isolators must be chosen according to the requirements.
- **Red** denotes Level 4, which stands for a high level of innovation represented by the gripper sub-assembly. The gripper must be designed specifically for clamping the dates palm tree which has never been done before. Even material selection becomes important in this case.
- **Black** colour indicates a need for research and development. This is used when something completely new must be designed.

Table 4
Comparison of Alternative Design Solutions of (a)Gripper Sub-Assembly, (b) Carrier sub-assembly, (c) Vibration sub-assembly, (d) Vibration Isolators.

(a)Gripper sub-assembly	**G1**	**G2**	**G3**	**G4**
Sketch				
Pad Surface Area	407.33 cm^2	897.74 cm^2	953.2 cm^2	709.33 cm^2
Material: **Jaw** **Clamping Arms** **Gripper Pad**	AISI 1018/SAE 304 Natural Rubber/Polyurethane	AISI 1018/SAE 304 Natural Rubber/Polyurethane	AISI 1018/SAE 304 Natural Rubber/Polyurethane	AISI 1018/SAE 304 Natural Rubber/ Polyurethane
Weight	(AISI 1018) 314.76 kg	(AISI 1018) 152.18 kg	(AISI 1018) 292.58 kg	(AISI 1018) 224 kg
Features	Frames to reduce weight	Extra support on the frame to increase contact surface area	Curvy shape with a higher surface area of the jaw	Jaw divided into 2 parts
(b)Carrier sub-assembly	**C1**	**C2**	**C3**	
Sketch				
Length, Width, Thickness	L = 53.5 cm, W = 50 cm, H = 9 cm, T = 2 cm	L = 50 cm, W = 50 cm, H = 8 cm, T = 10 cm	L = 64.8 cm, W = 68.6 cm, H = 8 cm,T = 5 cm	
Weight (Isolator not included)	(AISI 4130) 22.8 kg	(AISI 4130) 64.23 kg	(AISI 4130) 45.09 kg	
Features	Rectangular frames with holes to reduce weight	Curvy structure to reduce stress concentration on edges	Rectangular frames with fillets	
(c)Vibration sub-assembly	**V1**	**V2**		
Sketch				
Weight (kg)	52.514	46.016		
Features	Curvy shape with mountings to integrate commercial vibrator, hydraulic cylinder and gripper sub-assembly	Extra support for more stability, support thickness is reduced to decrease weight		
(d) Vibration Isolators	Spring type	Chain type	Elastomeric	
Sketch				

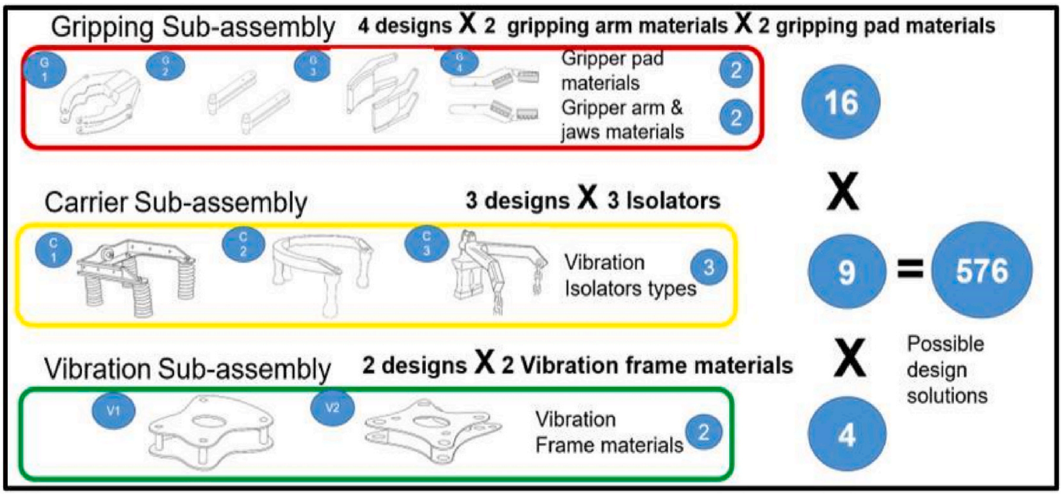


Fig. 6. 576 possible design Configurations generated.

3.5. Identify sub-system targets

To produce the best possible design solution, it is necessary to identify clear objectives and targets for each sub-system. This also prevents waste caused by over-engineering. These targets are defined based on the key values identified in the first phase. The sub-system targets that were identified for designing the dates harvesting machine are illustrated in Table 3.

3.6. Define the feasible region of design space

In the activity, a design space is created by the authors to have a clear boundary between which all the conceptual designs are created and then evaluated. The constraints are set based on the design requirements and previous knowledge. It was made sure that there is no over-constraint as that would prevent innovation. Several boundaries were generated for each sub-assembly of the dates harvesting machine as well as for the entire system. For instance, the maximum length for the whole system set by the authors was 140 cm based on the field study conducted as there are irrigation areas around the tree that need to be considered. Similarly, the material of the carrier sub-assembly should have a minimum tensile strength of 500 MPa for high strength. Fig. 5 depicts the feasible region for the design space.

3.7. Phase 3: Develop concept sets

In this phase, a set of alternative design solutions for each sub-assembly was developed and explored for the “dates harvesting machine”.

3.8. Create sets for each subsystem

In the activity, alternative conceptual design solutions were developed for each sub-assembly based on their level of innovation. The key value attributes, sub-system targets, and their feasible regions were considered while developing those designs. The design solutions were developed specifically for 1) Clamping Arm with jaw and gripper pad, 2) the Carrier frame with vibration isolators, and 3) the Vibration frame.

While designing the gripper sub-assembly as shown in Table 4-a, the contact surface area with the tree trunk, material properties, and cost were considered. For carrier sub-assembly as shown in Table 4-b, strength, and stiffness of material were considered as it is the main sub-assembly on which the entire machine is mounted. Also, the vibration isolator types were considered based on the frequency range and load-bearing capacity. Similarly, for the vibration frame, stability, and its integration with the commercial hydraulic vibrator and gripper were considered. As a result, a set of four grippers were designed with two varied materials for the jaws and the clamping arm, i.e., low-carbon steel AISI1018 and stainless steel SAE304, and two materials, i.e., Natural Rubber and Polyurethane for the gripper pads based on the key value attributes of design performance, safety, and cost, see Fig. 6.

For the Carrier sub-assembly, the team generated three design concepts made of a low-carbon steel AISI4130, due to its high strength as the carrier mounts the entire machine. The three different vibration isolators that can be used are Spring type, Chain type, and Elastomeric type, see Table 4-d. Likewise, for the vibration frame as shown in Table 4-c, two designs were generated using different steel materials AISI1018 and SAE304.

The design space of the “dates harvesting machine” shown in Fig. 5 could generate 576 distinct potential design configurations (also shown in Fig. 11-a) as shown below:

Fig. 7. Field Study conducted by the team at a dates farm in Saudi Arabia.

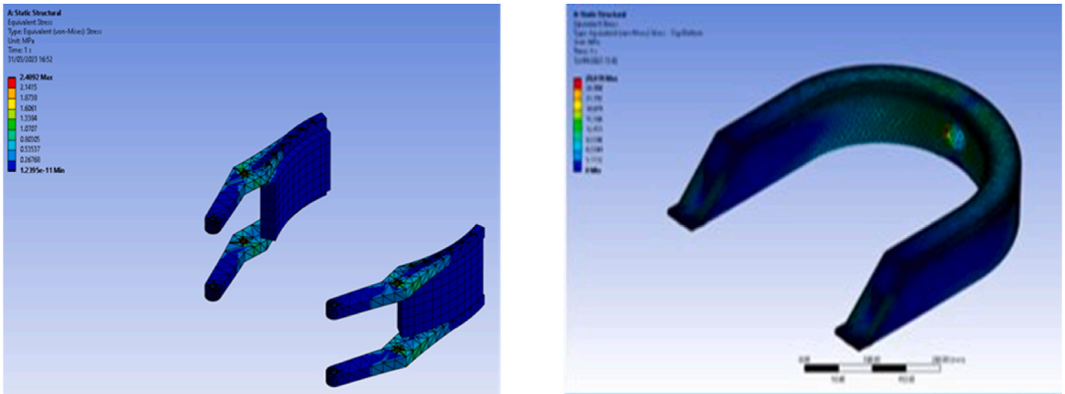


Fig. 8. Stress analysis of Gripper "G3" and Carrier "C2".

(4 × 2 × 2 Gripper Sub-assembly) × (3 × 3 Carrier sub-assembly) × (2 × 2 Vibration frame) = 576 Possible design configurations.

The research team conducted a field study as shown in Fig. 7, at five farms in the city of Al-Ahsa, Saudi Arabia to validate the design parameters with different stakeholders and confirmed the right progress of the results of the alternative conceptual design solutions for the dates harvesting machine.

3.9. Explore subsystem sets: prototype and test

In this activity, all the conceptual design solutions were analysed to test their reliability. The results obtained through the analysis are used later to eliminate the weaker design solutions and to narrow them. For this case, stress analysis was performed using Ansys to get the stress generated and deformation in each sub-assembly designed. Fig. 8 shows stress analysis of a clamping arm "G3", shown in Table 4-a and a carrier frame "C2", shown in Table 4-b. The CAD models were designed on SolidWorks. Similarly, the stress analysis was performed for all the grippers and carriers with their respective selected materials.

Several Trade-Off Curves (ToCs) [48] have been generated, as shown in Fig. 9, based on the data obtained from the stress analysis of all the alternative design solutions of the gripper and the carrier sub-assemblies as shown in Fig. 8 to aggressively narrow down the alternative design solutions [30]. This is done to define the feasible region identified for the design space as shown in Fig. 5 and hence, the highlighted region in the ToC represents the feasible region. The designs lying within this region are explored further and the rest are discarded for further exploration. For instance, according to the sub-system target, the minimum contact surface area of the jaws of Gripper sub-assembly was kept to 800 cm^2, and the maximum stress in the gripper must be less than 2.6 MPa. Similarly, for carrier sub-assembly, the minimum factor of safety was kept to 3 and the maximum stress that should be 100 MPa. The designs lying within this region, i.e., G3-AISI1018, G2-AISI1018, and G3-AISI1018 satisfy both criteria and hence, are chosen to be explored further. Similarly, for the carrier frame, C3 was discarded since it lies outside the feasible region of the ToC.

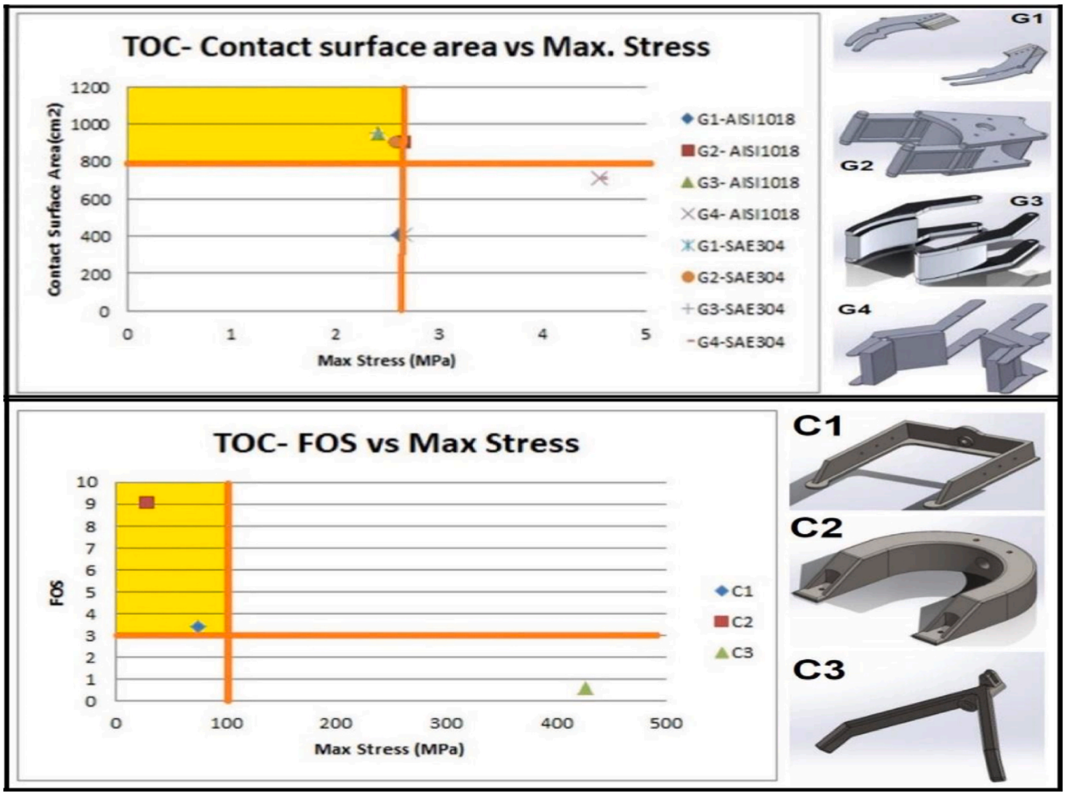


Fig. 9. ToC for (a)Gripper sub-assembly, with stress values (MPa) 2.62,2.67, 2.41, 4.55, 2.67, 2.59, 2.4, 4.57 and surface area (cm^2) 407.33, 897.74, 953.2, 709.33, 407.33897.74953.2, 709.33 (b) Carrier sub-assembly, with stress values (MPa) 74.77, 28.02, 426.44 and factor of safety, 3.39.9, 0.59.

The Vibration Isolator solutions were narrowed down by selecting the relevant properties of stiffness, greater deflection, ease of availability, cost, and greater load capacity [50]. This led to the selection of 'Spring Type Isolators' as shown in Table 4-d for the carrier frames C1 and C2. The use of ToC helped to narrow down 576 alternative design configurations (Fig. 6) into 48 possible configurations as shown below:

(3 × 2 Gripper Sub-assembly) × (2 Carrier sub-assembly) × (2 × 2 Vibration frame) = 48 Possible Design Configurations (also see Fig. 11-b).

3.10. Phase 4: Converge on system

In this phase", the integration of sub-assemblies was explored based on the knowledge gained from the previous phases of the set-based design process model. The alternative design solutions of all the sub-assemblies of the machine were explored further to finally converge to the final design solution of the dates harvesting machine.

3.11. Determine set intersections

In this activity, the final design configurations of the dates harvesting machine were generated based on the material properties of the gripper and the vibration sub-assemblies.

Material properties are chosen to narrow down the possible design configurations based on the sub-system targets shown in Table 3 and the defined feasible region for design space, shown in Fig. 5. The material properties were taken from Ansys Granta software. For the clamping arm, jaws, and vibration frame, as shown in Table 4, the materials chosen were Stainless Steel SAE304 and low-carbon steel AISI1018. Since the yield strength of AISI 1018 is greater and its density is lesser than SAE304, AISI 1018 was chosen. Similarly, polyurethane was rejected for the gripper pads since it has a lower coefficient of friction and a higher Young's modulus than natural rubber. These parameters were chosen because the pad needs to be elastic and have a high coefficient of friction in order to grab the rough tree surface securely and prevent slippage. As a result of this activity, possible design solutions were narrowed down from 48 to 4 as shown in Table 5, which is calculated as follows:

(1 Gripper Sub-assembly) × (2 Carrier sub-assembly) × (2 Vibration frame) = 4 Possible Design Configurations (also see Fig. 11-c).

Table 5
The narrowing down of conceptual design solutions into 4 configurations.

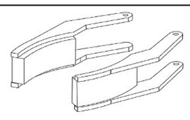
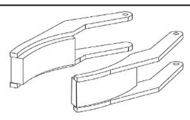
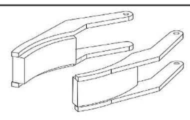
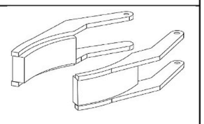
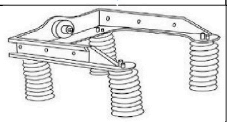
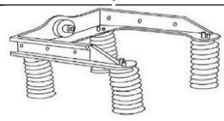
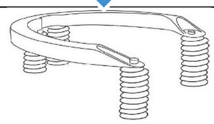
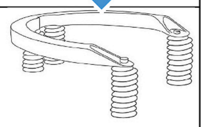
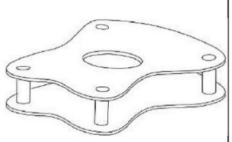
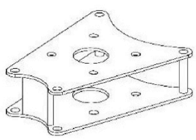
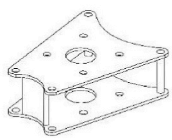
All proposed alternative sub-assembly design concepts				
Sub-system	Alternative Solution 1 (G3C1V1)	Alternative Solution 2 (G3C1V2)	Alternative Solution 3 (G3C2V1)	Alternative Solution 4 (G3C2V2)
Gripping sub-assembly				
Carrier Sub-assembly				
Vibration Sub-assembly				

Table 6
Evaluation of potential dates harvesting machines configurations based on their key value attributes.

DESIGNSolution	Design performance	Safety	Cost
G3C1V1	1. More stress in this carrier compared to other. 2. High strength material 3. Vibration frame is heavier	1. Firm grip on tree without damaging 2. More deformation in carrier 3. Vibration frame less stable	1. Carrier frame requires more machining and nuts and bolts
G3C1V2	Vibration frame is less heavy	Vibration frame is stable	Vibration frame requires extra machining
G3C2V1	1. Carrier frame gets less stressed. 2. High strength material 3. Vibration frame is heavy	1. Safe for trees 2. Less deformation on carrier	1. Comparatively less cost of carrier frame
G3C2V2	Vibration frame is less heavy	Vibration frame is more stable	Extra machining cost for vibration frame

3.12. Converge on final set of system

In this activity, the four design configurations were narrowed further to a single solution as only a single solution can be designed in detail. This narrowing was based on the knowledge captured in previous phases based on loads of importance from the key value attributes against the four potential design configurations and is shown in Table 6.

To obtain the final optimal solution for the dates harvesting machine, a PUGH matrix was used. It is a quantitative tool that assesses all the criteria with their weights [51]. Table 7 depicts the scores and rating criteria used in this case for the PUGH Matrix and the weightage calculation for all the designs. For example, the design "G3C2V2″ shown in Table 5 had a rating of 9 for design performance as it satisfies most of the values within it, 7 for safety as the stress and deformation generated in this case are less, and 5 for cost as it requires extra machining cost for carrier frame and extra material cost for the vibration frame support. These rating values were

Table 7
PUGH Matrix, with the highlighted configuration representing the final optimal design solution for dates harvesting machine.

Key Value Attribute	Importance (%)	G3C1V1	G3C1V2	G3C2V1	G3C2V2
Design Performance	40.63	5	5	7	9
Safety	38.83	5	7	7	7
Cost	20.54	9	5	7	5
Total Weightage	100	5.8216	5.7808	7	7.4018
SCALE	1-Less Impact	5-Moderate Impact		9-Target fully met	

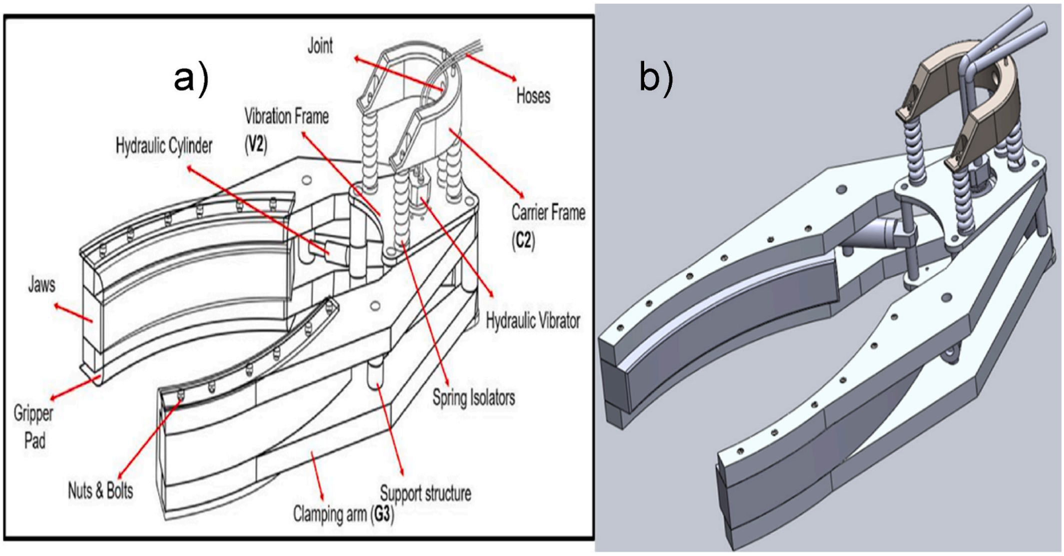


Fig. 10. a) Final design solution with detailed specification of dates harvesting machine, b) CAD Model of dates harvesting machine.

assigned after analysing the fulfilment of the key value attributes as presented in Table 6. The total score for the configuration "G3C2V2" is calculated as follows:

$(40.63\% \times 9) + (38.83\% \times 7) + (20.54\% \times 5) = 7.4018.$

The weightage calculation for all other designs were evaluated in a similar manner. Therefore, the configuration "G3C2V2" (also see Fig. 11-d) was chosen to be the best possible solution from the 4 design configurations identified after narrowing down. This is released to the final specification with detailed design in the next phase.

4. Discussion

After executing all the activities of the set-based design model, the final optimal design of the dates harvesting machine is released

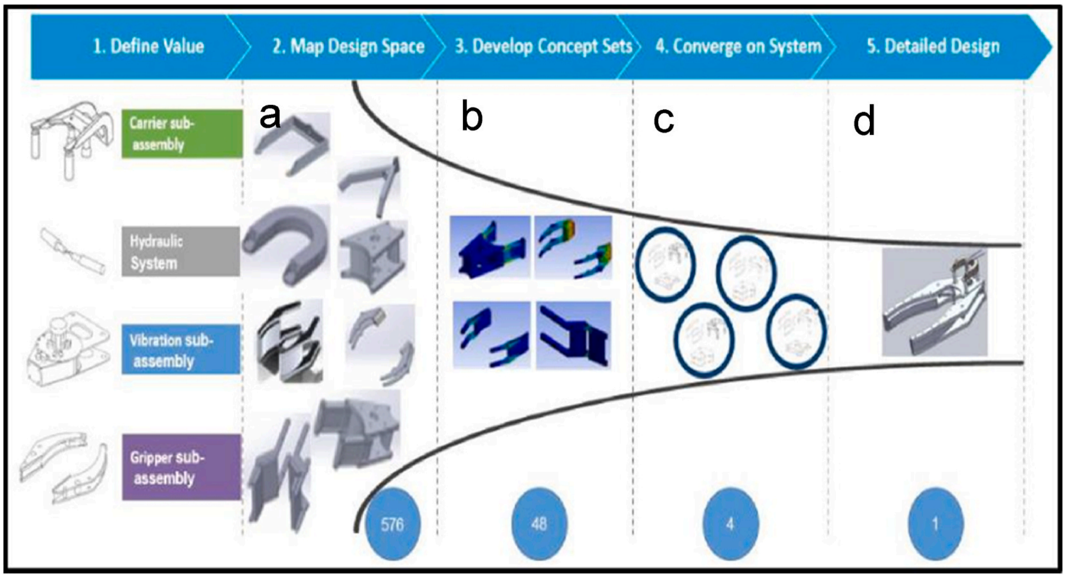


Fig. 11. Progress of designing and narrowing alternative designs of dates harvesting machine after every phases using the set-based design model.

as shown in Fig. 10-a and Fig. 10-b as a CAD model developed through SolidWorks. From the previous phase, "G3C2V2" was identified as the best possible design solution as it mostly satisfies the key value attributes. The material of the clamping arm and the vibration frame is AISI 1018 whereas the carrier frame is made of AISI 4130. The geometry of the clamping arm is curvy so that it can grip the tree firmly. Fillets are provided wherever necessary to avoid stress concentration. The gripper pad made of natural rubber is provided to prevent damage to the tree trunk and the machine as well. Spring type vibration isolators are provided for shock absorption. The overall length of the machine is 123 cm, width of 72 cm and the minimum tree diameter that can be clamped is around 30 cm.

The progress of designing and narrowing the sets of alternative design solutions using the set-based design process model is shown in Fig. 11. The results of the study showed that the use of set-based design methodology improved the efficiency and effectiveness of the design process for the dates harvesting machine. The iterative process allowed the authors to explore and analyse alternative design solutions, which ultimately led to a better final design. The SBD approach also enabled the authors to consider a wider range of design options and identify areas of weakness or inefficiency in the design that was refined through the iterative process. The innovation and knowledge level has also increased by applying this approach as it led to the creation of 576 distinct and innovative design configurations based on the key value attributes. This could provide an opportunity to explore further designs within the design space for future research as well. Those designs were analysed and evaluated which led to the creation of an optimal design solution for the dates harvesting machine.

5. Conclusion

The paper presented a detailed, well-structured Set-Based Design (SBD) process model based on well researched and identified principles, and its systematic application in a real industrial setting of dates harvesting machine (DHM). The successfully application of SBD has addressed the significant challenges associated with the labour-intensive and inefficient process of harvesting dates, a crucial economic activity in many countries including Saudi Arabia. The proposed dates harvesting machine design, developed through a meticulous process of literature review, architectural design, and iterative set-based design activities, represents a ground-breaking approach in the realm of fruit harvesting machinery. The SBD approach allowed for the exploration of a vast design space, resulting in the generation of 576 potential design configurations, which were systematically narrowed down to 48 and further to 4 optimized solutions. The narrowing down was based on a combination of trade-off curves, solution performance, and the key value attributes of 'design performance,' 'safety,' and 'cost.' The integration of the analytical hierarchy process and the PUGH matrix played crucial roles in this selection process. Field studies and engagement with local stakeholders affirmed the urgency and practicality of the DHM. In terms of efficiency, the DHM has the potential to reduce harvesting time from 30 to 40 min per tree with 4–6 workers to just 5 min per tree with only 3–4 workers, marking an impressive 83% time reduction. This not only enhances labour efficiency but also offers a cost-effective solution for small and medium-scale farmers through rental options, while large-scale farmers can make substantial investments for enhanced efficiency and safety. This research not only contributes to the agricultural sector but also advances the understanding and application of Set-based Design in the development of complex systems, setting a valuable precedent for future endeavours in lean product development and innovative design solutions. Future work will be the fabrication and testing of the dates harvesting system shown in Fig. 1-b and the design of cleaning and packaging sub-systems with it.

Data availability

No data associated with this study has been deposited into a publicly available repository as all the relevant data is already included in the paper.

CRediT authorship contribution statement

Priyansh Khandelwal: Writing – review and editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Ahmed AL-Ashaab:** Writing – review and editing, Supervision, Project administration, Investigation, Conceptualization. **Nirav Manishkumar Oad:** Writing – original draft, Software, Methodology, Formal analysis. **Venkata Surendra Kumar Masetty:** Writing – original draft, Software, Methodology, Formal analysis. **Pei Yan:** Methodology, Formal analysis, Data curation. **Mahmoud Abdelrahman:** Writing – review and editing, Resources, Project administration, Conceptualization. **Abdullatif Ali Alkhateeb:** Visualization, Validation, Resources, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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