Conceptual Design of Hemp Fibre Production Lines in Virtual Environments

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ABSTRACT

Increasing demand for hemp fibre requires sustainable manufacturing methods to produce the fibre in high quality efficiently. The existing hemp fibre production lines are inefficient with the high energy consumption. This paper introduces the conceptual design of hemp fibre production lines. The conceptual design and evaluation are conducted in virtual environments. A conceptual search and evolution method is described for the design of two types of the fibre production lines. Virtual environments are built to evaluate prototypes of the conceptual design and to simulate operations of the proposed production lines. Design visualization and concept evolution are achieved in the virtual environment. It is proved that the proposed design has the better performance in terms of cost, product quality and energy efficiency.

Keywords: conceptual design, hemp fibre production, virtual environments.
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1 INTRODUCTION

Hemp fibre is a natural renewable material with the potential to substitute carbon fibre and glass fibre [1]. With the increasing demand for high quality hemp fibre, processing methods of the hemp fibre have been developed in previous decades. Fig.1 a) shows hemp swaths in the field after harvest, b) is a non-scaled simplified scheme of the hemp stem cross section. The innermost layer of hemp plant is the pith, surrounded by woody material known as core. Outside of this layer is the growing tissue which develops into core on the inside and into the bast fibre on the outside [2]. Hemp fibre has to be separated from the hemp plant, called decortication. Hemp handling from field to fibre includes field operations and central processing. Field operations may include harvesting, retting, baling, and transporting bales to a processing plant. Central processing of hemp for fibre may include bale unwrapping, pre-cutting of hemp stalk, conveying, decortication, and cleaning. Increasing demand for the hemp fibre requires sustainable production methods to produce fibre in high quality efficiently. So far, the hemp fibre production is a labor-intensive operation. Current methods of hemp fibre processing are not efficient with the high energy consumption. The decortication and associated processes are to be improved for the industrial scale production. This research is to generate conceptual designs for hemp fibre processing to meet industrial needs.

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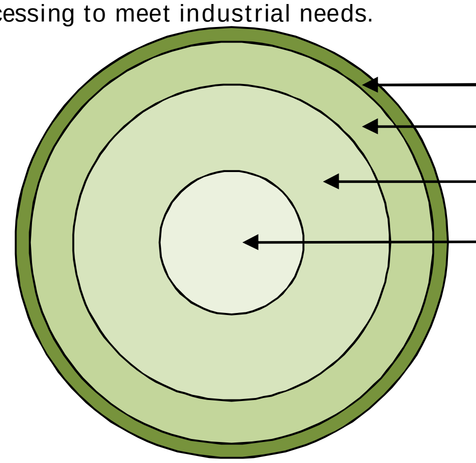


b) (not to scale)

Fig. 1: a) Hemp swaths, b) Simplified scheme of a hemp stem cross section.

Conceptual design is an important step for the final design success. Conceptual design identifies customer needs, establishes target specifications, generates design concepts, and tests the concepts before the decision of final specifications. Conceptual design normally performs economic analysis, compares benchmark competitive products, builds and tests proposed models and prototypes [3]. Methods to conduct conceptual design include brainstorming, axiomatic design, TRIZ or Theory of Inventive Problem Solving, etc. [4, 5]. A direct way to find a design solution may be the trial-and-error method [6]. Brainstorming is commonly used for quick problem solving as a natural style of human mind. However, these methods are unstable and unpredictable, and may require a significant time to search the solution. TRIZ or Theory of Inventive Problem Solving was originally developed by G. S. Altshuller and his colleagues [7]. They summarized common features from different creative work and patents to predict solutions of problems. The TRIZ guides designers to analyze problems and contradictions with provided directions for solutions. It has been successfully applied in many areas of engineering design.

Sustainability has become a critical measure of design in recent years because of the increased awareness of environmental problems and resource depletion [8]. Sustainable design promotes the minimum environmental and social impacts while maintaining economic benefits. There is a wide variety of indicators for sustainable design and manufacturing [9]. One of the important indicators measures the energy used in a process of production.

Compared to product design, production line design deals with not only equipment used in the production processing, but also the collaboration of all workstations in the production. One of the challenges is the concept description and evaluation. Description of a design concept may use a sketch, or a rough 3D model, often accompanied by a brief textual description. Methods of the concept evaluation have to be able to communicate concept, measure customer response, and interpret the result. Virtual environments (VEs) provide feasible tools to evaluate the design concept.

VEs are featured with visualization, interaction and usersô immersion. VEs have been the cost-effective tools in the evaluation of design concepts with the better description in 3D visualization using the virtual operation and testing. Many engineering applications have used VEs in the design verification and performance validation.

In this research, two types of conceptual hemp fibre production lines are proposed. One is for the short fibre processing from both retted and unretted hemp, and the other is for long fibre from retted hemp. The concept design and evaluation are conducted in virtual environments. Problems of the existing fibre production are analyzed. TRIZ method is used to find solutions to overcome bottlenecks of the design. Conceptual designs of hemp fibre production lines are proposed according to principles of TRIZ. The design evaluation and improvement are achieved in a VE, EON Studio.

Following parts of the paper are organized as follows. Section 2 reviews research in the hemp fibre processing, conceptual design, TRIZ method, and VE applications. The integration of TRIZ and VE is discussed in Section 3. Section 4 describes problem analysis and design criteria of hemp fibre production. Section 5 introduces the conceptual design of hemp fibre production lines. Conceptual prototypes simulation and evaluation in virtual environments are discussed in Section 6, followed by conclusions and further work in Section 7.

2 LITERATURE REVIEW

2.1 Hemp Fibre Production

There are hemp fibre production lines built for laboratory tests or industrial applications. A flax fibre pilot plant was developed by USDA and Czech Flax Machinery [10]. A commercial òLin Lineó developed by Temafa GmbH is able to process both hemp and flax straws [11]. A commercial production line built by VDE has the capability to handle 6.6 t/h straw bales with 1.92 t/h maximum output fibre [12]. The existing fiber processing equipment is mainly adopted from other manufacturing equipment. No one has really designed the hemp production line using analytical methods, or systematic approaches. There are two major challenges in the hemp fibre production: the fibre is hard to be separated from the stem as the fibre is attached tightly to the stem of hemp plant, and the fibre is in tangle which causes the fibre wrapping on rotating machine parts. Furthermore, the hemp processing needs to be improved for the fibre quality, production capacity, and waste reduction.

2.2 Conceptual Design and Virtual Environments

Conceptual design is an iterative process in the development of a problem solution, including following stages for concept generation, concept evaluation, and concept approval [13].

- Define the problem and customer needs
- Research previous solutions and expert opinions
- Generate ideas
- Converge on the best solutions
- Approve final concept or refine concept through iteration of previous steps

Product conceptualization is responsible for more than 70% of the total cost incurred during product life cycle [14]. Conventional techniques require designersô experience in the concept search, which may not explore solutions enough to generate the best result. The concepts are typically represented by various levels of abstraction, incompleteness and uncertainty [15]. To model products or processes in conceptual design, aspects such as function, structure, shape, behavior, sustainability and service are typically considered. A design concept can be incomplete as something is not yet known by the designer. Tools developed usually focus on individual aspects [16]. A concept design basically performs following processes [17]:

- Translating needs into functionality
- Develop performance metrics for requirements
- Finding a model and assessing behavior

Interaction is very important between designers and the solution to evaluate the design concept. Conventional CAD tools do not have all necessary capacities to support designers in conceptual design [15]. Visual representation provides a natural, flexible, and quick method for designers to express and communicate their creative ideas about the shape and functionality of a product. Visual interpretation can be used for evaluation. It gives designers direct access to the intuitive assessment of the design concepts against design specifications [18].

Virtual environments or VE-based systems permit designers to interactively improve design concepts. Recent advancements in high-speed computer hardware and VE technology provide opportunities to link the more creative conceptual design with the product detailing and engineering analysis [19]. VE-based simulation has been proved an efficient and flexible concept exploration method [20]. Pellens et al. used VEs allowing non-experts to participate in the conceptual design. Their approach uses ontologies, incorporating domain knowledge and high-level modeling concepts in the VE [21].

2.3 TRIZ and Applications

TRIZ is a knowledge-oriented method for conceptual design [22]. One important principle of TRIZ is the use of evolution patterns. A pattern represents a direction to idealize the problem. The first step of the solving problems using TRIZ is to idealize the problem without considering the weakness, cost or barricades [23]. The ideal final result is approached when all benefits are reached with least costs or harms. Using patterns helps the concept development in the direction to generate ideal final results. Once ideal final results are approached, TRIZ requires the encountered technical problem identified in the format of contradictions. The fundamental concept of solving problems is to eliminate the contradictions [7]. Two groups of contradictions can be classified using TRIZ: technical contradictions and physical contradictions. Technical contradiction is the classical engineering **ò**trade-off**ó**. Physical contradiction is also called inherent contradiction for an object with opposite requirements. After contradictions are identified, the tool for eliminating contradictions can be applied. **ò**TRIZ-contradiction matrix**ó** provides references for solving problems. Using the contradiction matrix, designers can identify up to 39 engineering parameters in both improving and worsening directions. Contradiction matrix then provides the recommended **ò**40 principles**ó** for specific contradiction combinations. There are also **ò**76 standard solutions**ó** related to the 40 principles providing more detailed ways of contradiction elimination [7, 22, 24]. The 39 features of TRIZ contradiction matrix have been increased to 48 features in recent years.

Finally, the solutions provided by the matrix can be transferred into a real design for solving actual problems. Fig. 2 indicates a flowchart of TRIZ in solving problems. However, there are also some weaknesses using TRIZ method. When improving and worsening features are selected, some of the elements in the contradiction matrix are empty so that the matrix cannot provide recommendation for such situations [5]. In addition, because of the complexity of translating practical requirements, constraints or criteria of design problems in TRIZ method, TRIZ contradiction matrix is known being difficult for applications [5].

TRIZ-based design methods have been conducted by many researchers. Design improvements are also achieved using TRIZ. The TRIZ method was applied in analyzing the modular fixture design for the complexity of machining components [23]. The controllability of automation was improved. A conceptual design of the packaging machine was developed to convert the real problem into substantiate function diagram of the process [25]. TRIZ was used in the descriptive design framework by Pham et al. [5], which can track the ideas throughout the design process. Shirwaiker et al. conducted a review on both TRIZ and axiomatic design and found that the compatibility of the two methods could be applied synergistically to achieve better solutions [4]. TRIZ is considered to be capable to generate innovative solutions, while axiomatic design has the function to analyze the effectiveness of solutions.

A manufacturing process can be improved by the guide of TRIZ if technical contradictions can be eliminated. Hsieh and Chen [22] designed a friction stir welding process using TRIZ as a problem analyzing and solving tool. Zhang et al. [26] studied the development of the cutting technology using the evolutional technology of TRIZ. Fresner et al. [27] used TRIZ for the cleaner production improvement. Mathis reported an example using the TRIZ method to improve the design of candy pouch [6]. The research used TRIZ as well as experiments in each design stage. However, the research is almost for individual product design. There is very little literature found in the conceptual design for an entire production system.

3 INTEGRATED TRIZ WITH VE

The integrated TRIZ and VE are proposed for the conceptual evaluation of hemp fiber production lines. The TRIZ method provides a tool to gain solutions for conceptual design problems. However, not all the recommended solutions can meet the need of real problems. Before transferring TRIZ solutions into the implementation, there should be a testing procedure to evaluate the solutions. However, testing in the real world is often time-consuming, expensive and sometimes even impossible. As VEs are featured with the system visualization, user interaction, immersive environment and information integration, various problems in design, such as design errors, collisions in operations, and inconsistency in material flows, can be detected in VEs. To avoid cost and time-consuming process to build proposed production lines, we use concept of the virtual testbed to test the design proposals. The concept generated from TRIZ is modeled and simulated in a VE. Detailed operations and feasibilities of the process are visualized for alternative configurations. A flexible, reconfigurable and reactive VE with capabilities in managing the design change is expected. As shown in Fig.3, a VE is proposed to assist the design evaluation to get the feedback from the concept design. The VE provides the virtual model to check TRIZ solutions with usersô interaction. The design concept is evaluated by simulating its working processing. The VE also guides the design in the TRIZ procedure to select other alternatives for the problem based on the concept evaluation. It includes TRIZ procedures shown in Fig. 2.

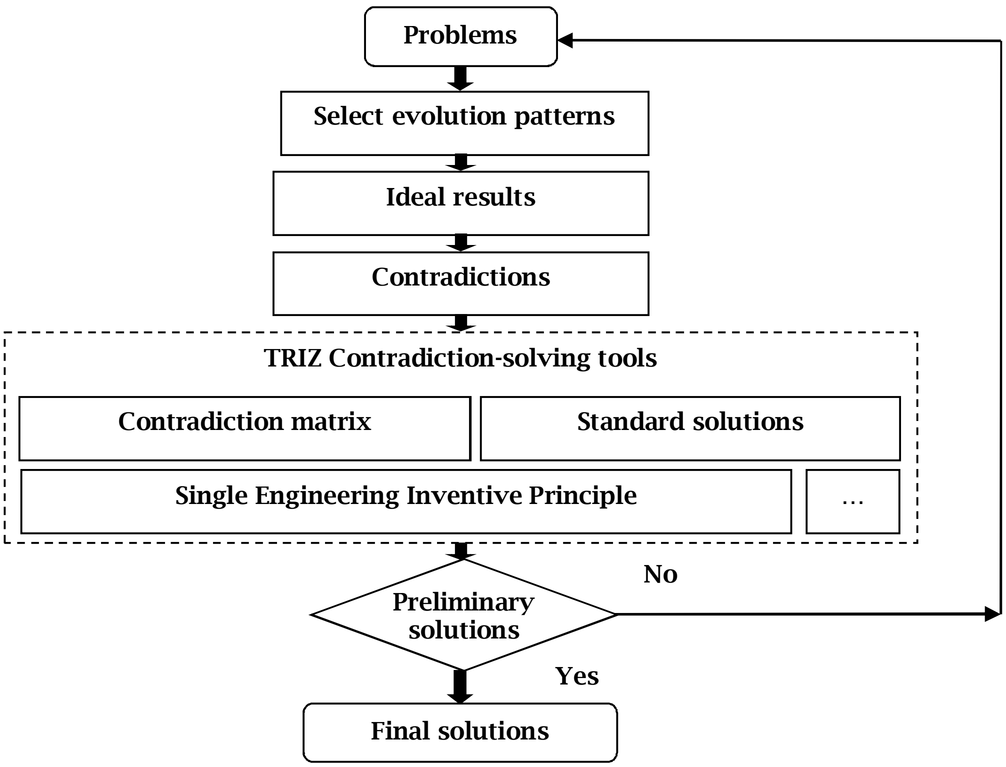


Fig. 2: Flowchart of TRIZ in problem solving.

4 PROBLEM ANALYSIS AND DESIGN CRITERIA FOR THE HEMP FIBRE PRODUCTION

Our design looks at the decortication and associated processes, named central processing production of the hemp fibre. Processes of pre-cutting, decortication, post-decortication are main components in central processing production. Other components such as metal detector, conveyor, and output fibre baler may be varied in different processes.

Hemp fibre processing requires a variety of components in the production line. The design of a hemp fibre production line has to consider not only the individual components to meet the processing requirement, but also the integrated performance of the entire system. Based on literature and the industrial investigation, performance measures of the hemp fibre production are decided as follows:

- Quality of the fibre processed
- Efficiency of machine, processing, and hemp handling
- Ratio of hemp production input and output
- Cost of equipment, material processing and handling
- Energy consumption

Therefore, an overall evaluation criterion (OEC) is used to measure the system performance. It includes above five major attributes of the hemp production as follows.

OEC = Q (Quality)+ Ef (Efficiency)+ R (Ratio)+ C (Cost reduction)+ Ec (Energy reduced) (1)

OEC provides directions to tailor the conceptual design of the hemp fibre production. Some problems in the hemp fibre production are found by analyzing the existing fibre production methods. One problem is that in order to gain clean fibre (the fibre free of cores), some additional processes are required. This would increase the processing time and the workshop size. Simultaneously, the power and energy consumption would be increased, making the procedure costly and less efficient. Productivity is also a factor considered. Processing speed may be increased if the machine speed is increased. However, more energy will be required to run the machine, and loss of the fibre may be increased due to the higher speed. More broken fibre may fall down as shives and be collected as waste.

Based on potential improving areas and related problems to meet a higher OEC, the new design is proposed by moving to following directions:

- Fewer processing stages,
- Relatively smaller size of machine dimensions,
- Less fibre waste along the processing,
- Simple structure to achieve better maintenance ability,
- Better controllability for adjusting machine performance on different hemp varieties,
- Less chance of wrapping or entanglement.

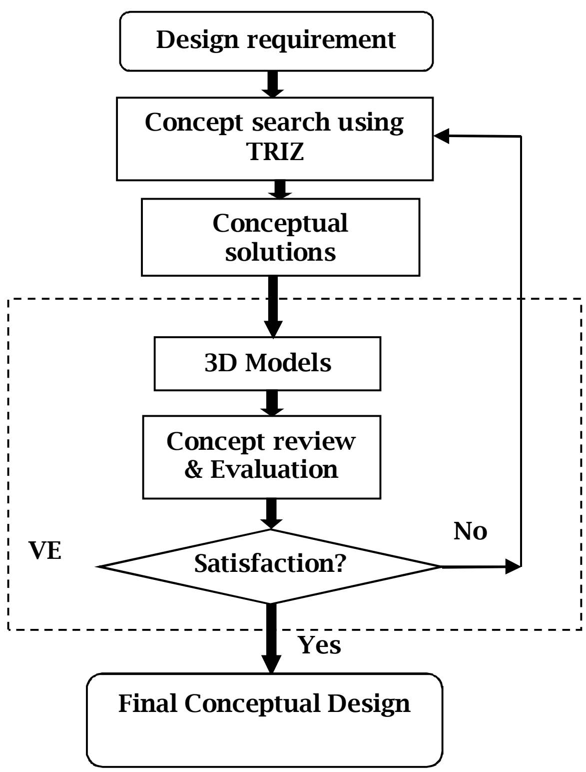


Fig. 3: Integration of TRIZ with VE.

So far we only consider the machine improvement for the decortication. Other devices are selected from the existing devices available in the market to complete an entire production line.

Two evolution patterns are chosen for the decortication machine improvement as follows.

- Transition toward micro-level and increasing use of fields.
- Increasing dynamism and controllability.

Five pairs of contradictions are abstracted from problems summarized in Tab. 1.

Improving feature	Worsening feature	Solution
#39 Productivity	#6 Area of stationary object	#17 Moving to a new dimension
#29 Manufacturing precision	#22 Loss of energy	#2 Extraction
#9 Speed	#22 Loss of energy	#35 Parameter change
		#14 Spheroidality ð Curvature
		#20 Continuity of useful action
#9 Speed	#29 Manufacturing precision	#10 Prior action
#29 Manufacturing precision	#36 Device complexity	#18 Mechanical vibration

Tab. 1: Selected contradictions and solutions from TRIZ contradiction matrix.

According to the TRIZ contradiction matrix, the decortication machine improvement was proposed [29]. However, these solutions can only generate the design directions without exact ideas. Based on the proposed concepts, possible models and shapes are built in the VE, and a preliminary evaluation is taken to assess the proposed conceptual model. At the conceptual design stage, no physical activities are available to test and evaluate the virtual prototype. It is also difficult to simulate the hemp material reaction due to the complexity of the bio-fibre material properties. The model evaluation is only based on the geometrical feasibility of machine operations. The energy consumption is based on data from literature and the lab experiment [30]. The production line configuration is improved based on the simulation feedback. This procedure is illustrated in Fig. 3.

For instance, during the long fibre decortication using roll crusher, brittle shives are crushed into small pieces. Though some of them will escape from the fibre easily, a considerable amount will still attach to the fibre, or entangle with the complex. Sending these undesired shives to further procedures will affect the degree of purification in the final product, while adding another device such as a sieve shaker specifically for removing shives will increase the complexity of the whole system. This brings the contradiction between improving ò#29 Manufacturing precisionó & worsening ò#36 Device complexityó. The idea of using high speed air fans is inspired by the TRIZ solution ò#18 Mechanical vibrationó, that air flow generates mechanical vibration which helps the removal of shives during the decortication in roller crusher without worsening the device complexity. The detail structures of the improved design are presented in the following sections.

5 CONCEPTUAL DESIGN OF HEMP FIBRE PRODUCTION LINES

Based on the previous discussion, two fibre production lines are proposed as shown in Fig. 4. One is for the short fibre processing from both retted and unretted hemp, and the other is for the long fibre from retted hemp. The short fibre production line consists of a bale unroller, a belt conveyor, a rotary cutter, a chain-type conveyor, a hammer mill, a second belt conveyor, a rotary screen, a third belt conveyor, and a carding machine. The long fibre production line consists of a ball unroller or a bundle opener, a belt conveyor, a roll crusher, a rotor cleaner, air fans, a second belt conveyor, and a linear impactor. Detailed descriptions of each component are discussed below.

5.1 Short Fibre Production Line

As shown in Fig. 5, conceptual models of the proposed solutions are built using AutoCAD. EON Studio, a VE modeling tool, is used to construct virtual environments for the concept testing and design evaluation. CAD models are imported into EON Studio for the VE modeling.

Bale unroller: It unwraps bales at beginning of the production with an inclined belt. The belt consists of a series of horizontal bars each having unsmooth surface to increase the friction between bales and bars. As single bale unroller may not provide the desired feeding rate to meet the capacity demand, the bale unroller is designed with a width of 4m to handle two hemp bales side-by-side simultaneously.

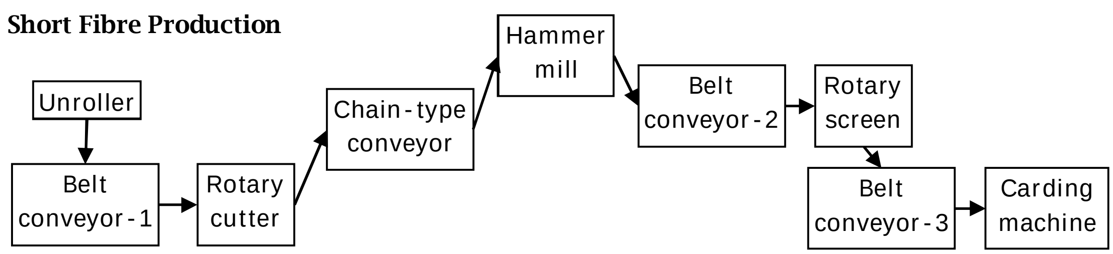
Belt conveyor-1: The loosed hemp stalk is discharged from the bale unroller to belt conveyor-1, a horizontal belt conveyor. The conveyor moves the loosed hemp stalk to a rotary cutter. The conveyor is placed horizontally under the outlet of the bale unroller, parallel to the belt bars.

Rotary cutter: The rotary cutter consists of two pairs of leading rollers. Around the rotor, the cutter head has 6 knives arranged symmetrically. If the running speed of the belt conveyor-1 is designed as 2 m/s and the rotational speed of the cutter is 1000 rpm. The theoretical output length of the materials from the rotary cutter is approximately 20 mm. To achieve longer output hemp length, 3 of the 6 knives can be used symmetrically to have a cutting length of approximate 40 mm.

Chain-type conveyor: Cut hemp stalk from the rotary cutter is discharged onto a chain-type conveyor, an inclined conveyor. It elevates the materials up and discharges them into the hopper above a hammer mill.

Hammer mill: The proposed hammer mill has a high capacity for the hemp processing. The machine dimension is designed based on the compatibility with other devices in the production line. The hammer mill has a screen to control the fibre size below the rotor. The bottom of the hammer mill is connected with a pipeline leading to a cyclone and a dust collector. At the end of the pipeline, an exhauster is linked to provide exhausting air. The working principle is that hemp stalk is impacted by the rotating hammers to become a mixture of free fibre and free core particles as well as fibres which are still attached to cores, then pass through the bottom screen, being sucked to the cyclone, and collected at bottom of the cyclone. Dust (fine particles) is collected by a dust collector.

Belt conveyor-2: It is mounted below the cyclone of the hammer mill, moving the mixture of fibres and cores to a rotary screen for cleaning. This belt conveyor has the same specification as the belt conveyor-1.



Long Fibre Production

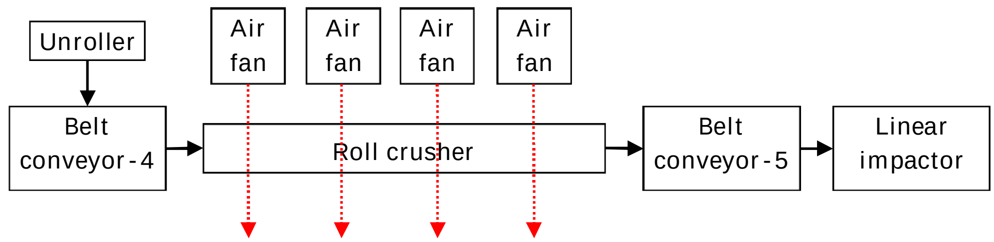


Fig. 4: Flowcharts of short fibre and long fibre production lines.

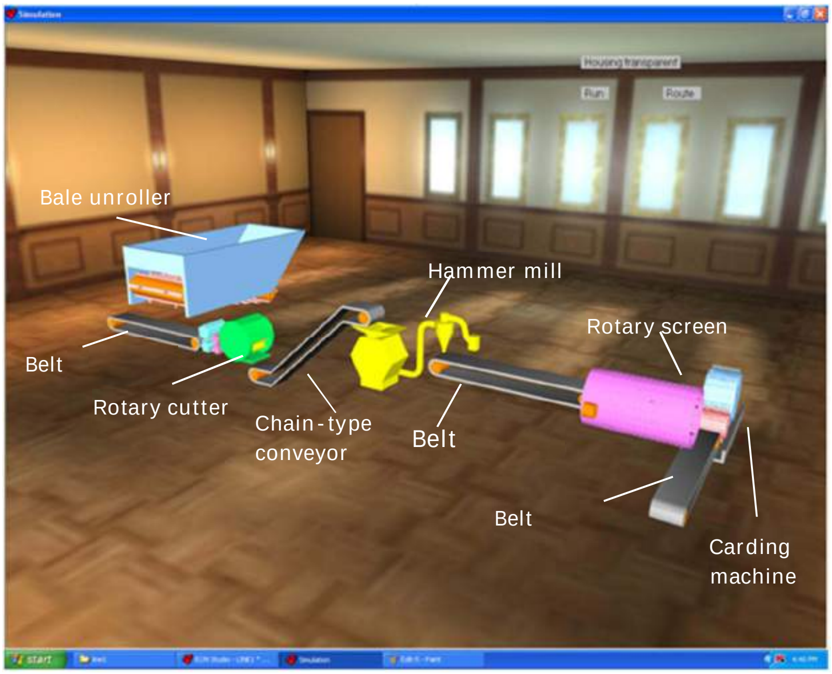


Fig. 5: Model of the short fibre production line.

Rotary screen: It is used to remove shives, and/or separate the material into different size fractions. It is designed with a diameter of 2 m and length of 3.6 m. Multiple screens can be used if different size factions are desired. The opening size and shape of the rotary screen can be varied according to the need.

Belt conveyor-3: It delivers the material from the rotary screen to a carding machine. This conveyor also has the same specification as the belt conveyor-1. It is placed below the outlet of the rotary screen.

Carding machine: It has two rollers with pins. Small roller has a diameter of 1 m, and rotates at a faster speed. It serves as a feeding roller. The pins separate the fibre attached to core. Large roller has a diameter of 2 m, and rotates at a lower speed. The fibre is caught by the pins along the roller surface in a relatively aligned way. Once the fibre accumulates to a certain amount, the fibre is removed using tools, for instance, brushes and or combs.

5.2 Long Fibre Production Line

Fig. 6 shows the conceptual model of the proposed solutions for the long fibre product line with following components:

Bale unroller or Bundle opener: It is the same as the one used in the short fibre production line. It is only needed when hemp is harvested in bales. If hemp is harvested in bundles, hemp stems in bundles have the same orientation to reduce the decortications effort and for less tangled long fibre. In this case, the bale unroller will be replaced by a bundle opener.

Belt conveyor-4: The hemp stalk from the bale unroller or bundle opener will be transferred by a belt conveyor-4. It has the same specifications as the belt conveyor-1, leading the hemp stalk to a roll crusher.

Roll crusher: The proposed roll crusher consists of two pairs of leading rolls, four pairs of crushing rolls. The leading rolls and crushing rolls are mounted with teeth to increase friction. The gap between the rolls of each pair is adjusted by the spring which can generate pressure between rolls and the materials passing through.

Air fans: Core is crushed into pieces while hemp stalk passes through the roll crusher. Air flow is introduced to assist the removal of small core and shives. Air flow is provided by four air fans installed above the roll crusher. Each air fan has 12 blades. Flow passes the gap downwards between roll pairs.

Rotor cleaner: Fibre is further cleaned by a rotor cleaner following the roll pairs. The rotor has a lot of long pins on the surface and rotates at a high speed. The rotating rotor impacts the output fibres from the roll crusher to further remove the core, especially for core still attached to fibre.

Belt conveyor-5: This is the same as the belt conveyor-1, installed below the outlet of the rotor cleaner to transfer the fibre to a linear impactor.

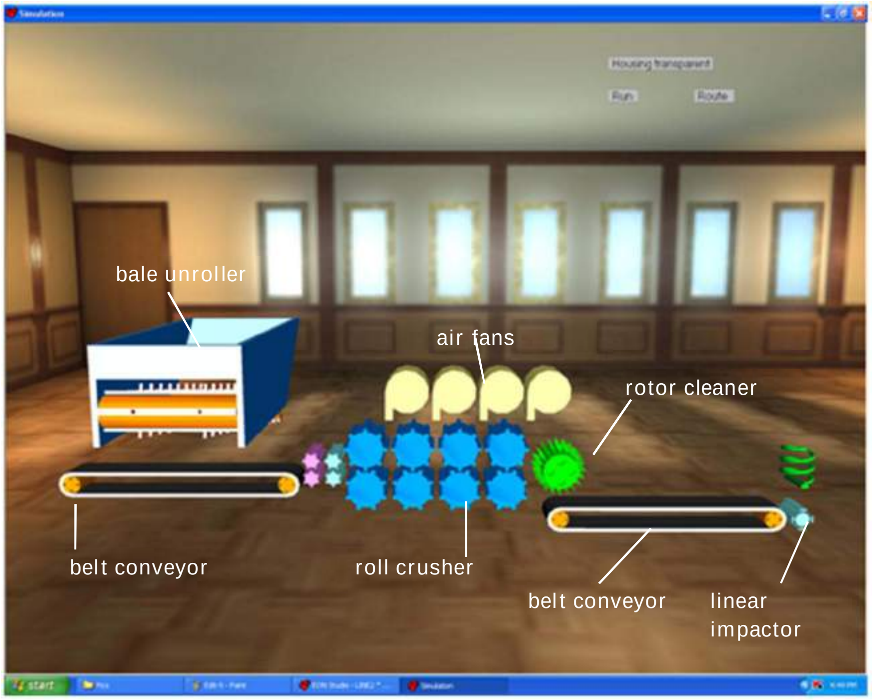


Fig. 6: Model of long fibre production line.

Linear impactor: It follows the belt conveyor-5. The impactor consists of a metal impact head connected to a spring, and a slow rotating rotor surrounded by four rubber pad bases. When the metal impact head reaches to the lowest point, it impacts on the fibre on the rubber pad base. This impact will further remove the core attached to the fibre. Then the metal impact head will go up as a returning run, and the rotor rotates 90° clockwise to move the fibre impacted forward for the next impact. Fig. 6 shows only one linear impactor. To achieve better effect, multiple impactors may be mounted one after another.

6 CONCEPTUAL PROTOTYPES SIMULATION AND EVALUATION IN VIRTUAL ENVIRONMENTS

Simulation models are developed in virtual environments to demonstrate machine structure and working mechanism, which provides opportunity for designers to conduct the cost-effective design evaluation. Fig. 7 is the VE framework built. Figs. 5 and 6 show the system user interface.

6.1 Model Review and Simulation

A variety of interactive operations are built in VEs for the design review and evaluation. For example, some devices in the production line have housing outside rotational parts. In order to observe the structure details inside, a òHousing transparentó simulation is created. It links to the òSmooth operatoró to change the transparency properties of the model texture. An example is shown in Fig. 8. By clicking this selection, the housing becomes 30% transparent, and the parts inside can be observed. Another function is the model detail, achieved by controlling a series of òPlaceó nodes triggered by òClick Sensoró as shown in Fig. 9. Selected examples of this function are shown in Fig.10.

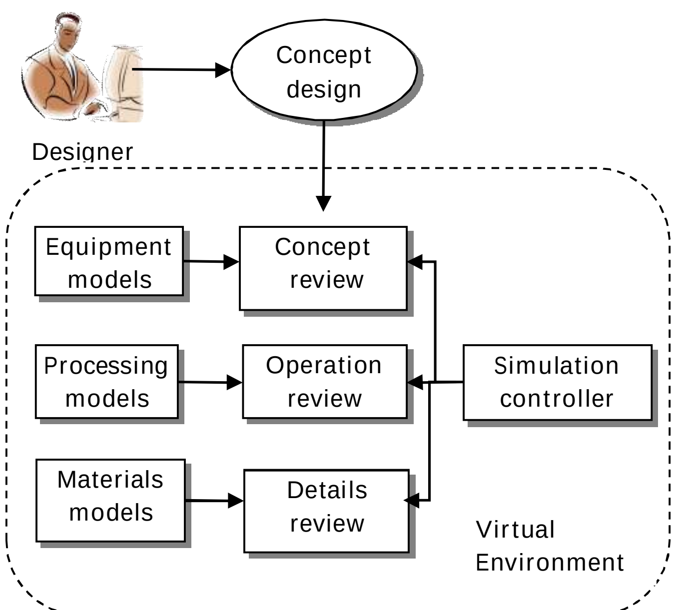


Fig. 7: VE framework.

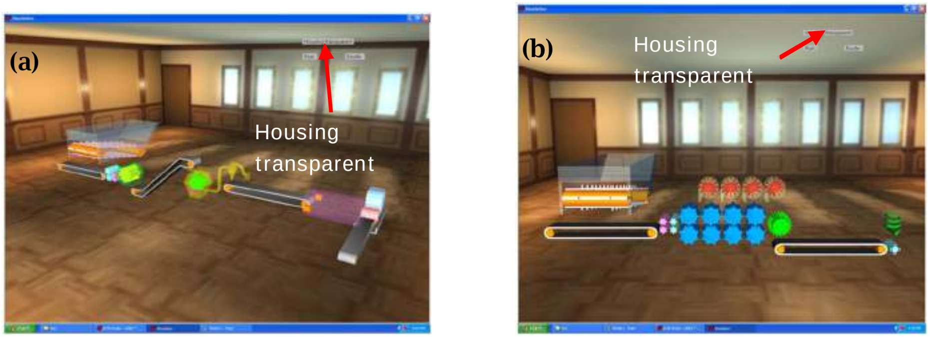


Fig. 8: Housing transparent function: (a) Short fibre production line; (b) Long fibre production line.

6.2 Operation Simulation

Operation simulation of the design is the key feature to evaluate the production configuration. The operation is achieved by controlling òTime Sensoró and scripts as shown in Fig. 11. òTime Sensoró generates signals to òScriptó to simulate the operation processing.

6.3 Material Flow Demonstration

Arrows with different sizes and shapes are used to represent the hemp stalks and fibre products. The movement of hemp materials through the processing is controlled by òRouteó. The selection of òRouteó will show material flows at different sections of the production line. Their movement represents how materials are transferred in the production processing. One example is shown in Fig. 12.

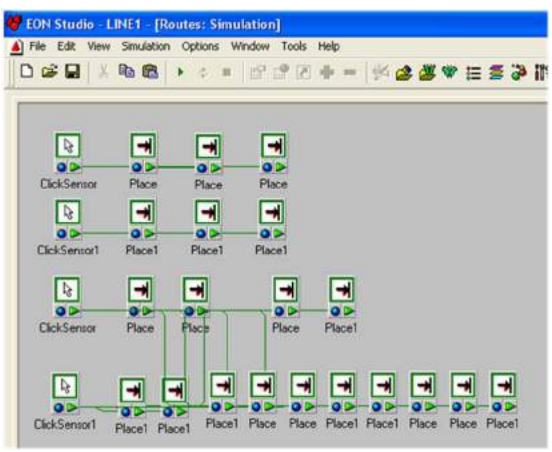


Fig. 9: Link structure of the model details control.

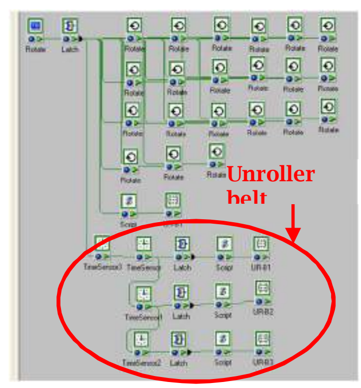


Fig. 11: Movement and rotation control

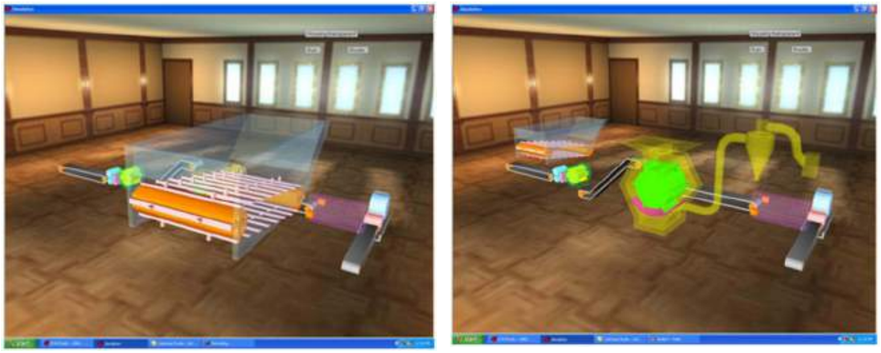


Fig. 10: Some details shown in the VE.

7 CONCLUSIONS AND FURTHER WORK

Two conceptual hemp fibre production lines are proposed in this research. The short fibre production line uses a hammer mill as the decorticator which is suitable for processing short fibres. Long fibre production line has a roll crusher as the decorticator to produce long fibres. TRIZ provides an effective tool for the concept search to guides us to analyze problems and solving contradictions. Simulation is developed in virtual environments to demonstrate the proposed concepts and production processing, which provides a cost-effective tool for the design review and evaluation. The proposed conceptual models can be used for the detail design of hemp fibre production lines. More data are to be collected for the energy consumption estimation to improve sustainability of the hemp fibre production. The VE was built using Eon Studio available in our VR lab. Other VE simulation tools will be considered with functions of the particle simulation for the material flow, shape and size changes in the production. A fiber production line may be constructed for the practical tests.

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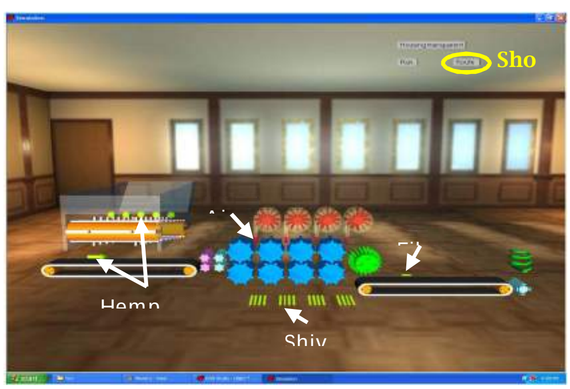

Fig. 12: Material route demonstration in long fibre production.

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