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Decision Support Based on Digital Twin Simulation: A case study in Distillery Industry

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Abstract

This paper presents a complete digital twin framework with the purpose to aid manufacturing ergonomics and control operations in distillery industry. The focus is on the design of a digital twin framework that manages the material flow in the real system based on ergonomics and resource efficient parameters of the manual operations. Preliminary experiments are done by applying the digital twin framework on a lab-scale case study and demonstrate the applicability of the proposed approach.

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Keywords: Digital twins; ergonomics; design

1. Introduction

This paper focuses on the design of a digital twin framework that manages the material flow in the real system based on ergonomics and resource efficient parameters of the manual operations in distillery operations. Designs focus on the ergonomics issue which affects operators the most when using a tool repeatedly and this causes Repetitive Strain Injury (RSI). In a previous work, ergonomic indices along with the use of digital tools were used within a design methodology to validate the tool against the redesign, [1]

The authors are now evaluated on a lab-case study the results of using the new design in the physical space by users.
Over the last 25 years, there has been a succession of small improvement steps in the brewing and distilling industries, resulting in lower labour, reduced consumption of raw materials, energy, and water, together with innovative solutions to effluent and by-product treatment.

Several companies are adopting a more digital approach to business in response to the increasing levels of complexity of modern products and systems, the distributed engineering and manufacturing of these products, and the rising expectations from customers and business partners,[2]. Using digital innovation to improve business processes, supply chain efficiency, agility, and sustainability has become a necessity for competitiveness,[3]. Several software packages can now be integrated to 3D modelling systems offering increased accuracy and alternatives and, again, contributing to a much less expensive design cycle,[4].

By integrating digital twin technology into their operations, distillery companies can improve efficiency, quality, and sustainability, ensuring their competitiveness in the rapidly evolving beverage industry,[5].

1.1. Whiskey Making Process

The whiskey making process was analysed in its phases and mapped against the manual operations performed in each of them. Six stages were identified and listed below:

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- Malting is the first step in the whisky-making process. Barley is soaked in water and distributed throughout a heated malting floor to germinate. This process activates the enzymes that change the starch into sugar once the mashing stage has finished. It is now called green malt and goes into a kiln for drying.
- Mashing is the second step of the process. Once dried, the malt is ground down into flour. Hot water is then added progressively as the vat increases in temperature. This creates a liquid known as wort. This stage is the one which requires carrying bags on a pallet, normally on a manual pallet lift. The bags are then emptied manually into the mash tun through manway.
- Fermentation is the third step. The wort is cooled down and transferred to washback. Yeast is then added which eats the sugar and therefore produces alcohol and other compounds. This process continues for two days where the now 'wash' contains 6-8% alcohol by volume.
- Pot stills is the fourth stage. The wash is transferred into custom pots where it is now distilled just under boiling point to remove the alcohol and other compounds to evaporate and then condense in a separate container. This continues until the wash contains 20% alcohol.
- Distillation is the fifth phase. The process of distillation happens twice. The first one is to divide the alcohol from the water, yeast, and deposit. It then moves to a different still called a low wine which removes other more volatile compounds and oils. At this point, the liquid known as 'the heart of the run' has 68% alcohol by volume.
- Spirit Safe is the sixth stage. All the liquids are tested by an experienced Stillman, it is then reduced to 63% alcohol. Finally, it is then poured into casks to begin the maturation process in large warehouses. The racked warehousing is a heavily manual operation which still require at least two operators at the time to be performed.

For this study we decide to use the racked warehousing removal and the bung removal using the design results in,[1]

1.2. Bung removal operation.

The methods for removing the bung from the cask has been the same for many years. The bung of the cask lives within the bung hole. This bung has been in the cask for a minimum of 3 years if the liquid inside the cask is to be called a Scotch whiskey. It has endured a range of different temperatures and pressures as conveyed in the maturation section of the review. Operators within the distillery use 3 main methods to remove the bung from the cask:

- Flogging the Bung: the method involves applying a striking force several times to the barrel which, depending on the condition of the barrel, could cause damage to the barrel and to the operator performing the task.
- Mechanical Methods: This method destroys the bungs meaning they cannot be reused. Rather than using this method to achieve a sample it is typically used when the whiskey is drained from the cask as shown in source 18 when the cask has been transported to the warehouse to the machine. The operator in the video rotates the barrel assuring it is bunging side up and aligns the screw part of the machine to the centre of the cask. The machine is then activated, and the bung is split in 2 and removed by the operator. The task can be seen to be very repetitive and doesn't require a skilled operator to perform.
  Bung Extractor: This method, along with the flogging of the bung, is one of the oldest methods for bung removal. The method involves using a specialised tool design to be driven into the top of the bung and then twisted down until the screw has sufficiently been driven into the bung. Then an operator applies a sharp upward force (if bung id facing up) or a lateral force (if the bung is 90° from the upright position). The process only takes a few seconds to complete however one a continuous line the process can quickly become repetitive leading to injuries.

1.3. Racked warehousing.

The racking system within a warehouse for a distillery company is something of importance to each distillery across the country even across the world. Whether the businesses are big recognisable brands or ones at the beginning of their journey to become pub familiar classics, everyone within this industry relies upon using warehouses to store their products for maturation. The intention of this report was to document how firstly the existing process works within one of these storage warehouses, for moving fully filled casks from the moment it's delivered into the whatever racking system the warehouse uses. Once this can be identified then ways of finding improvements to this process of movement could be produced, these improvements could be slight changes but if they could help to reduce the stress-load on the warehouse crews for moving these casks around then the projects main aim would be achieved. This study a would give companies perhaps food for thought for helping their staff's physical health and reduce wastes within this sector of the industry. The thought and attentions will also lap over and involve how lean fundamentals/approaches can have a better more positive effect on this occurring process and bolster the company's abilities to control and monitoring health and safety, and quantified time and cost to carry out this operation.

How the racking systems could be re-designed or perhaps how whisky casks could be made from lighter material just to satisfy what is already in place, regarding how many crew members it takes to move these batches of casks etc.is not explored at this stage. The idea of these design changes is possible but the posture evaluation through the digital twin framework was the focus of the operation.

2. Digital twin simulation

Design thinking process integrated within digital tools were used in previous work,[1]. This methodology offers a solution-based method to resolving problems. This allows for complex problems with little detail to be tackled effectively by understanding them with the primary focus the requirements of the human and building a framework around them. The physical space was created on a lab-scale basis to collect data on the two main manual operations identified in section 1.2: a) bung removal and b) racket warehousing.

Fig.1 shows the digital twin simulation framework, described in the following sub-sections.

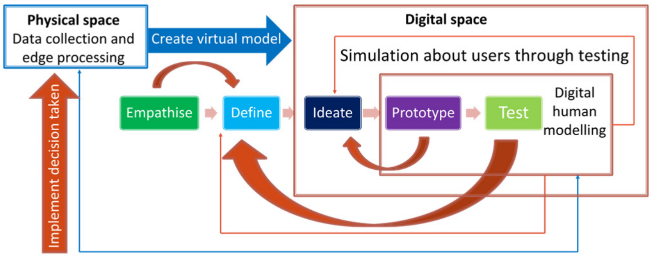

Fig. 1. Digital twin simulation.

2.1. Design methodology.

In previous work the authors presented a design methodology based on design thinking process integrated within digital tools.

Fig.2 was the chosen design for the new tool in [1].

The design allows for the support leg to be made in line with the body allowing for the screw piece to be driven into the bung. The support is then placed onto the cask, or the hoop and the rounded shape of the support's face allows for the stresses to be spread across the face rather than at a point like if the face was not rounded. The handle is on a pin allowing the user to maintain a grip of the tool whilst rotating it. The handle is then pulled upward, and the support and the screw stay parallel to each other.

Fig. 2. Bung removal tool,[1].

2.2. Physical space

To create the physical space, we use a tun cask (1000 liters),[6], a 90th percentile male operator who was familiar with the operations to perform. However, the operator had to be trained before to be familiar with the new equipment to wear.

As hardware the following items have been used:

- HTC Vive: the Vive consists of a headset, two controllers, and two infrared laser emitter units. The headset covers a nominal field of view of about 110° (approximately 90° per eye) through two 1080 × 1200 pixel displays that are updated at 90 Hz[7],.
- Perception Neuron motion capture (Mo-Cap) system. This system provides the ability to perform calibrated full body inertial motion capture in real time, while streaming and logging kinematic data into their proprietary software (Axis Neuron), the suit has several operating modes which include single arm, upper body, and full body capture. Whitin this study the system was configured in the upper body 16-neuron mode.

The choice of the upper body mode and the number of neuron mode was driven by number of joints involved to perform the operations and the calculations of the ergonomics indices to assess the performance.

The human aspect of the tool is imperative to the design of the tool as the user's feedback and overall safety is key,[8], [9]. The tool must meet the regulations that have been outlined for safe use. The user will be using the tool constantly and the forces felt within the operation must be limited to help mitigate the stress/strain on the operator, [10].

The tool is manually driven or contains its own power source for remote operation and the tool can be used by one hand so that one operator is enough to use the tool.

Fig.3. Physical space set up.

2.3. Digital space

Aiming to show the applicability and the effectiveness of the framework showed in Figure 1, a case study is described here, related to the bung removal task carried out in a laboratory, where the task has been defined and performed.

Figure 4 shows the working scenario reproduced in a simulation environment.

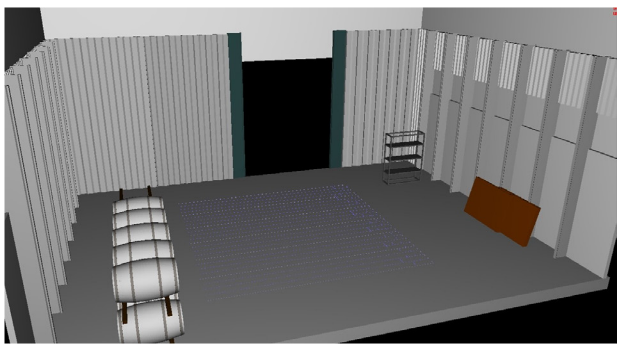

Fig. 4. Digital space set up.

2.4. Digital human modelling

Process Simulate human was used for the simulation of the tools within a realistic working environment. The software allowed for a computer-generated human to be implemented into a warehouse environment and the bung removal operation carried out with both sets of tools.

Both simulations started the same with the human at the bung and then prompted to grab the tool from the table a few feet away. The tools were then brought to the cask and placed onto the cask and screwed into the bung. An upward force of 200N was then applied to the tool simulating the forceful removal of the bung.

Fig. 5. (a) 90th percentile operator while carrying out the bung removal OP assuming the posture PEI_2; (b) 90th percentile operator while carrying out the racking warehousing OP assuming the posture PEI_3.

3. Case study results

By simulating the operations (bung removal and racked warehousing), the workers' postures were evaluated using the Posture Evaluation Index (PEI), developed, and illustrated in,[1]. The PEI integrates the results of the Low Back Compression Analysis (LBA), the Ovako Working Posture Analysis (OWAS), , and the Rapid Upper Limb Assessment Analysis (RULA), in a synthetic non-dimensional index able to evaluate the "quality" of a posture:

$$PEI = \frac{LBA}{3400} + \frac{OWAS}{3} + \frac{RULA}{5} \quad (1)$$

In Table 1 simulation results are reported for the bung removal operation. The operation was repeated for ten times to familiarize with the new scenario and to have enough data to calculate the ergonomic index.

When comparing the data from the different simulations developed in the new framework the Lower Back Analysis of the original design is seen to be higher than the one performed only using the digital human modelling design,1692(on average of the ten operations repeated) >417. This results positively favour the new approach showing that the user is greatly under the 3400N threshold set out by the software.

Ovako Working posture analysis showed a yellow rating of 2 on the evaluation. It is not extreme in both simulations however ways to limit these issues could be performing the operation with the cask elevated from the ground or having the operator kneeing or sitting to limit the amount of bending the back must endure whilst over the cask.

The Rapid Upper Limb Assessment for both designs showed negative results in both cases. The original design received a score or 7 the highest possible score on the scale indicating that action must be taken to correct these actions. The new design didn't score too well either with it ranking a 6 on the scale. This is slightly better than the current design but again action should be taken to correct this. A new posture would be suggested for the operations as it would be beneficial in both cases and especially in the new design as the force required wouldn't be the same in comparison to the current design as the support would be utilised more.

The comparison of the PEI indices shows that the new design generating a value acceptable below 3, whereas the data for the new design generated a value of 1.989 for the index by using only the digital space,[1]. These values show that the new design performs better in these ergonomic parameters compared to the old design.

Table 1 Ergonomic analysis and PEI evaluation

Bung removal op	LBA (Newton)	OWAS	RULA	PEI
OP1	1,573	4	6	*2.23*
OP2	1,975	2	6	2.65
OP3	2,287	2	5	2.34
OP4	1,868	3	5	2.75
OP5	1,673	4	6	*2.23*
OP6	1,263	1	6	2.40
OP7	1,807	1	6	2.56
OP8	1,904	2	5	2.23
OP9	1,085	1	6	2.35
OP10	1,486	4	6	*2.46*

Table 2. Joint angles related to reference PEIs

PEI	(a) Back inclination angle	(b) Right shoulder rotation	(c) Right arm extension
1	0°	0°	95°
2	20°	29°	110°
3	60°	125°	155°

Overall, the design is seen to perform better however changes could still be made to accurately represent the tools performance. More testing could've been performed with different percentiles, genders and regional variations being tested within the software,[11]. Prototyping was tested however restrictions prohibited the chance for physical models to be made and tested in person. Restrictions also hindered the chance to meet and talk to the staff within many distilleries and warehouses and really gauge how they felt about the tool and what changes they would like to see within the design.

Finally, Table 3 shows results achieved for the racking warehousing operation. Through the simulation we were able to identify a better posture for rolling the cask from the line towards the rack and back for loading and unloading purposes.

Both values are acceptable however if we consider the repetitiveness of the operations per day, particularly in big distillery the reduction of the PEI of 7% is a great achievement.

Table 3. PEI Results comparison for racking warehousing.

Operation	LBA	OWAS	RULA	PEI
	1715	2	7	2.465
	552	2	5	1.689

4. Conclusions and future works

The main aim of the paper has been fulfilled with the validation of the bung removal operation in the distillation processes. This aim was achieved by developing a decision support based on digital twin simulation.

The methodology represents an innovative approach to use digital twin simulation to improve efficiency of resources, ergonomics, and parameters control in distillery companies.

Preliminary results allowed for ideas to improve the current manufacturing processes in distillery industry.

Future research will explore methods to improve the user interface with features to determine feasible operation routes of a product automatically.

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