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Portable rapid visual workflow simulation tool for human robot coproduction

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Abstract

Within the European Factory-in-a-day project, the aim is to improve communication between automation integrator and factory owner, in their analysis of feasibility and appropriateness of automating a manual task. A visualisation tool with preconfigured workflows and working principles, with specific focus on efficient human-robot coproduction workflows can improve this process. This paper describes the Workflow Simulation Tool, which is part of the Human-Robot Coproduction Methodology, currently in development. The tool encompasses a portable tablet PC, which runs a visual modelling environment combined with a handheld 3D scanning solution. The tool also features pre-modelled template layouts, implementation of a checklist of persistent notes and portable visual documentation. The tool's appropriateness was iteratively validated in collaboration with automation integrators. This evaluation showed that offering an interactive visual simulation enriches the dialogue during conceptual design and helps in revealing requirements that otherwise only appear during or after implementation.

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1. Introduction

With the advent of more affordable and more easily programmable robot manipulators [1], many manual tasks in production lines are being reconfigured by automation integrators to accommodate robots and other automated equipment alongside humans in order to increase productivity. However, every production task is unique when the involved products, machines, facility layouts and human resources are considered. This results in a unique integration problem every time, requiring a project-based approach to develop a solution. The design phase of a conventional automation integration project has three main stages: Conceptual design, Detailed design and Design review [2]. Using the current analysis and design methods, the generation of requirements and the development of a suitable solution can take up to several months to complete [3]. In our previous work, we performed a case study targeting automation integrators during the initial stage of this process, as part of Factory in a Day project [4]. Our analysis suggested that the observed approach lead to suboptimal communication, and by extension a limited exploration of solutions.

In this paper we introduce and evaluate a Workflow Simulation Tool (WST), which is developed to support in the conceptual design stage, with specific focus on iteration and co-creation [5]. The tool is intended to be used by specially trained integrators in the context of rapid automation projects, such as envisioned by the Factory in a Day project. Before a production line can be installed and programmed, the integrator visits the site, observes the current workflow, acquires the requirements and makes a general layout for the new envisioned production line, all within a single visit. The WST intends to facilitate the discussion, by providing means to quickly and effectively visualise and document the simulation, allowing for faster iterations, thus arriving at an appropriate solution to an integration problem sooner.

After a short state of the art survey, this paper encompasses a description of the theoretical workflow, the architecture of the developed tool and the evaluation.

2. Related knowledge

2.1. Literature on the design of manufacturing systems

Publications covering the development of better tools for the design of manufacturing systems can be found in various fields such as Manufacturing Technology (MT), Production Research (PR), Computer Integrated Manufacturing (CIM), Computer Aided Process-Planning (CAPP) and Human-Machine Systems (HMS). For the aims of the WST, we cover recent research that contributes to the following two topics of interest;

2.1.1. Visual workflow modeling

The design of products and production lines in factories has benefited from CAD for decades [6]. As a part of this, the modelling and simulation of production line workflows are performed using a mixture of visual methods, such as Discrete Event Simulation [7] and recently also Virtual Reality [8]. By using these methods, engineers can create complex logical models and immersive virtual representations of workflows in complete manufacturing systems or parts of production lines and simulate their performances over time. Yet, these helpful methods used in the design phase of production lines still require high skill and long processing times [9]. This is a barrier for the wider implementation of these methods and intelligent manufacturing systems.

2.1.2. Increasing speed of design

In order to increase the speed of design of manufacturing systems, a rapid analysis method for manual production lines was introduced by [2]. In this work, the extension of the rapid analysis method and the software towards mixed production lines consisting of humans and machines is suggested. In their work, [10] have highlighted the importance of ‘Expert Systems’ in process planning as their approach allows the capturing of implicit and explicit knowledge from experts. A similar approach could increase the speed of analysis and generation of a list of

requirements. Another approach [11] demonstrated that template based design could be an effective and fast approach for the conceptual modelling of production systems. However, the proposed layout planning solution was limited to a static design and lacked the conveying of the dynamics of the workflow. More recent work [12] stated the need for tools with shared repositories that target specific manufacturing contexts.

2.2. Action research: challenges in design of production lines

Through qualifying performance in a relabeling station [4] and additional interviews with experts throughout our contextual inquiry, a list was compiled that contain some of the most common challenges in the rapid design of production lines:

- Acquiring and translating spatial constraints into specifications
- Incompatibility of vendor-specific software packages
- Distribution of knowledge
- Loss of recorded knowledge
- Difficulties in acquiring latent/tacit knowledge
- Communication challenges (misunderstandings, assumptions)

2.3. Vision and Objectives for the Workflow Simulation Tool

The WST is developed as an aid for some of the challenges faced by automation integrators in their design process as described in Section 2.2. The main intent is to facilitate the discussion between an automation integrator and a client through faster design iterations aided by 3D visualisation. Translating a functional specification (client's wishes) into a technical specification (integrator's recommendation) requires a close collaboration of the parties involved across all disciplines.

In order to address the abovementioned challenges and open issues mentioned in Section 2.1, several technologies are integrated into the WST. As a base for the WST we propose the use of CAD software that is capable of displaying animated workflows in designed production lines. Furthermore, to enable its user to transfer more real-life data into the model of the production line in a quick way, 3D scanning is integrated into the WST. Also, the possibility to create easily exchangeable and viewable digital files with embedded 3D graphics is integrated into the WST to streamline feedback steps between requirements, design and presentation of concepts. Additionally, the WST has access to online component and template repositories in order to enable the automation integrator to quickly model production lines based on standard components (e.g. different types of robot manipulators, transportation cells, operators, products, controllers). As a final goal, the integration of process, equipment and product specific expert knowledge in the form of short questions is built into the WST in order to trigger discussion between client and integrator and reduce the amount and requirement of knowledge acquisition in following iteration cycles.

The choice of the underlying technologies is merely a recommendation (justified in a Section 3), and was found optimal for the prototype used in further testing.

3. Architecture

3.1. Theoretical framework: HRC Design Methodology

The WST has been ideated as one of the instruments of the HRC Design Methodology (Figure 1). This methodology is being developed to support the design process of designers of manufacturing systems in which humans and machines work together. The tool is used in the 'Human-Robot Coproduction Design' and 'Productivity Based Optimization' phases of the methodology. The methodology allows iterative loops. Therefore, based on the assessment of the simulation results coming from the WST, a new iteration can be executed.

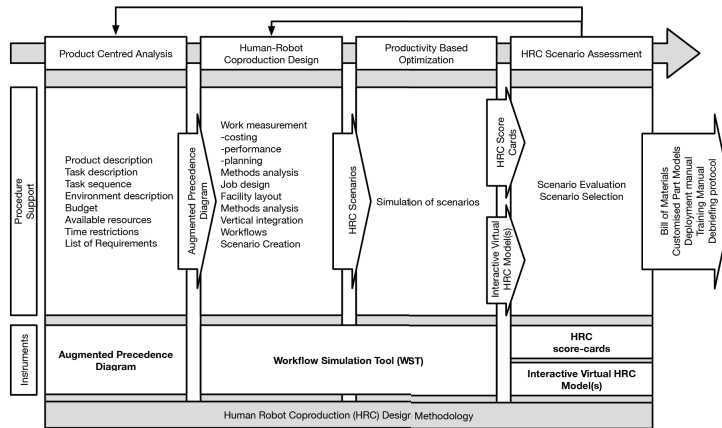


Figure 1 - HRC Design Methodology

The integration of the mentioned technologies such as 3D Scanning, Online Repository, Checklist, templates and 3D PDF and the operationalization of the WST as part of the HRC Methodology can be seen in Figure 2.

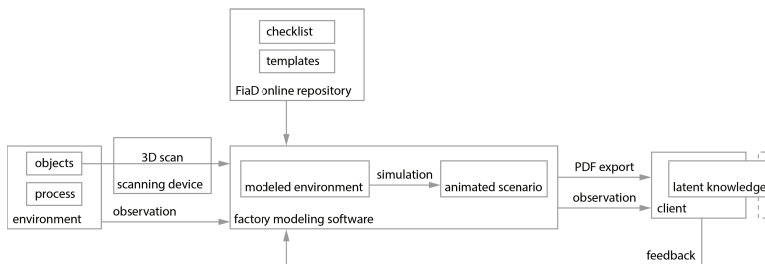


Figure 2 - information flow of the WST

3.2. Enabling technologies and design rationale

The WST is a combination of readily-available technologies (software and hardware), outlined below.

3.2.1. Factory modeling

The criteria used for the selection were: animated 3D visualization and simulation, drag & drop factory-centric configurations, rich library of components from various manufacturers, and portable documentation export. A number of alternatives were considered. Visual Components [13] was chosen as it is a highly extendable CAD solution, offering drag-and-drop 3D visualisation of animated material flow and offline robot simulation within a single package. In being manufacturer-agnostic and allowing the user to easily expand the library of *components* (e.g. robot manipulators, conveyors), the software facilitates in simulating a material flow without finalizing the exact technical specification. This was theorized to lend itself highly towards an iterative design process. A built-in feature of interest was the PDF export, which converts the simulation into an animated 3D environment within the popular portable file format, allowing for a richer documentation, and theoretically more fruitful communication, without requiring from the recipient any additional software. Also, in researching the appropriateness of the broader WST, Visual Components proved to be an adequate basis for testing additional features that were implemented in this study.

Table 1. Comparison of factory planning software.

Product	Description	Features
Visual Components 4.0 [13]	Manufacturing simulation, factory floor planning	Library of components, Python API, PDF export
Delmia, Dassault Systemes [14]	Manufacturing simulation, process planning	Steep learning curve
FlexSim [15]	Manufacturing simulation	expandable with C++
RoboDK [16]	Simulation and offline robot programming	Library of components
V-REP [17]	Factory automation simulation	Cross platform
Simio [18]	Simulation, production planning and scheduling	Non-factory specific
Simulink-SimEvents [19]	Discrete-event simulation engine	Non-factory specific, 2D only

The WST relies on a basic Visual Components training courses for the user to get acquainted with the concepts and user interface of the modelling and simulation package. Said training, be it workshop or self-taught through online resources [20], can take approximately three days, and is recommended for the user to get acquainted with the concepts and user interface of the modelling and simulation package.

3.2.2. 3D scanning

Translating spatial constraints into specification requires an appropriate accuracy in simulation. Obtaining measurements of the environment and 3D models of objects therein is best achieved using a non-contact 3D scanner. The obtained data was then transferred and imported into the factory modelling software.

The WST comprises of the readily available and affordable 3D scanning product, Structure Sensor from Occipital [21], which utilizes structured light PrimeSense technology [22]. The sensor connects to a range of devices, and offers near out-of-the-box combination with an Apple iPad (through the Occipital Scanner app [23]), affording a colour 3D scan.

Table 2. Comparison of non-contact 3D scanners.

Technology	Device	Notes
Structured light (PrimeSense)	Occipital Structure Sensor [21] + iPad	iOS device
Structured light (RealSense)	Wacom MobileStudioPro Enhanced [24]	Windows device
Structured light (PrimeSense)	Asus Xtion PRO [25]	Wired to a computer, no display
Structured light	Artec Eva [26]	Wired to a computer, no display, expensive
Structured light (RealSense)	3D systems Sense [27]	Wired to a computer, no display
Structured light (PrimeSense)	Kinect v1 + FARO SCENECT [28]	Wired to a computer, no display
Time of flight	Kinect v2 + 3D Builder [29]	Wired to a computer, no display, low quality
Photogrammetry	Fuel3D Scanify [30] + Mobile package	Requires time to process
Photogrammetry	Single photo camera	Requires considerable time to process

The combined 3D scanning solution is cordless, and allow the user to walk around while scanning an object. Upon completion, the 3D model is immediately made available to the user on the screen. The software automatically detects and removes the floor and minimizes the otherwise required post-processing. The resulting model can then be exported in a common, open .OBJ 3D file format.

In recreating the WST the choice of a 3D scanning solution is up to the automation integrator, their preference and budget. A number of alternatives are presented in Table 2.

3.3. Pilot implementation

The pilot implementation of the WST is visualized schematically in Figure 3. The Visual Components software is developed for the Microsoft Windows operating system, and requires an appropriate device. A choice was made for a touch-screen laptop, for its portability and interaction capabilities, encouraging co-creation. The preference for an online repository, as a means for delivering the templates and checklist held within, was motivated by communicating to the participants the early development stage of those additions (as opposed to the quality of the commercial software), further encouraging candid feedback. Cloud synchronisation hopes to further suggest future growth of the contained assets. The access to the online repository and importing the 3D scanned model required a wireless Internet access device.

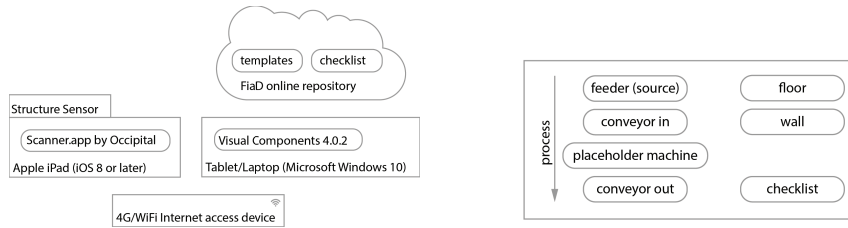


Figure 3 (left) - Deployment of the WST; Figure 4 (right) - Components present in a template

3.3.1. Online repository

The stock Visual Components library offers individual components (e.g. conveyors), and complex demo layouts. The former require configuration, while the latter are too complex to act as a basis for conversation (rather used as demonstration of software capabilities).

The WST online repository offers basic pre-made layouts, consisting of the essentials needed to illustrate the most basic material flow: source – manipulation – destination. Figure 4 presents all components used for a simple pick and place system, which can be positioned according to the client's needs. At the time of writing the pre-made layouts include: 'Pick and place', 'Bin picking' and 'Machine tending'. This can be further extended with HRC patterns [31]. The template further includes a checklist module, a floor and a single wall.

Upon dragging the layout into the 3D environment, the simulation can be started immediately. This offers a rapidly available conversation piece, as the client is presented with an, albeit rudimentary, animated visual representation of the factory flow within seconds. The simulation based on the template can then be iteratively modified, starting with the findings of the first round of client feedback.

3.3.2. Checklist module

The WST dynamically adds a list of property fields to various components in the 3D environment. These added fields act as mere simple notes, which the user takes and stores within each component.

The intention behind the checklist is to remind the automation integrator to inquire about aspects which are of importance and relevant to the simulation on the screen (e.g. 'how consistent is the size of awaited product?'). A predefined checklist covering all possible questions was found too overwhelming and at the same time too constricting to the varied needs of automation integrators, thus the list of items is stored in a JSON file separately [32][33], allowing a user to easily create a custom list of such reminders. The values entered by the user for each of the checklist items can be found once again in the exported PDF. This ensures these notes are stored alongside the animation of the 3D simulation in a portable file, sent to the client and further within their organisation. This decreases the risk of loss of information, further increasing the effectiveness of each iteration of the problem-solving process.

4. Application examples

In the process of selecting solutions and identifying opportunities the project team supported itself with two project cases. A bakery hoped to better meet the demand for a seasonal pastry, but due to its small size, limited space and low series production it lacked experience with mass production processes and related equipment. Second, a custom stationary company explored the possibility of automating selling made-to-order custom laser-etched boxes for felt-tip pens, giving individual customers the freedom to select both the color and box decoration.

The following steps outline an example interaction between an automation integrator and a client (Figure 5), and how the WST could be used to facilitate their project intake meeting. Prior to the meeting with the client, the automation integrator has installed Visual Components 4 on the Windows device, and added [34] as a source within the eCatalog panel.

Having received the verbal introduction to the current production method, the integrator selects a desired automation template (e.g. the ‘Pick and Place’ template) from the repository and drags it into the 3D environment (Figure 6). The layout is ready for a simulation; pressing the play icon initiates an animated simulation. The visualisation is made more concrete by adjusting the process durations and positions of the conveyors, robot manipulators or other machines to better accommodate the problem specification. In order to place the process cell in context, the dimensions thereof can be adjusted through changing the sizes of the floor and wall, included in the template. The grey production-machine-placeholder acts as a link in the production chain, but misses the visual representation, which is provided through the subsequent import of a 3D scanned object (Figure 7).

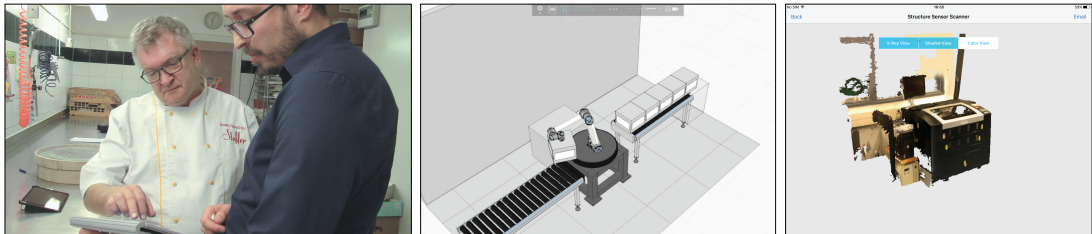


Figure 5 (left) - current production method explained; Figure 6 (center) - bare ‘Pick and Place’ template; Figure 7 (right) - 3D scan result

Using the iPad and the Occipital’s ‘Scanner’ app, the user follows the instructions on-screen to acquire a 3D model. As the user walks around the object to record all sides, the progress of the scan is presented live on the iPad screen. Upon completion, the 3D model is immediately available for preview and export. After importing the resulting 3D geometry into Visual Components, the model is positioned atop the placeholder machine.

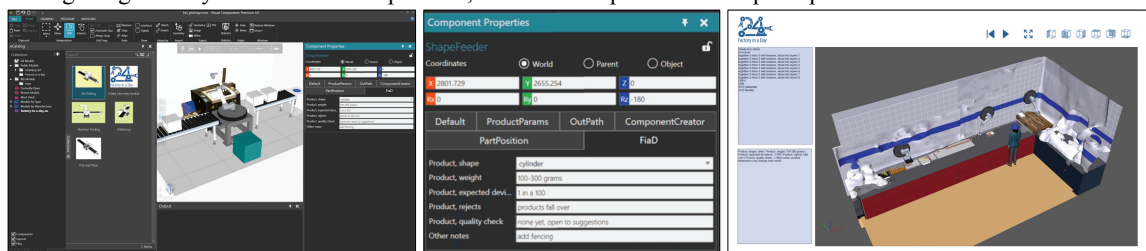


Figure 8 (left) - Visual Components interface, left: library, middle: interactive 3D environment, right: property inspector; Figure 9 (center) - Checklist items in the property inspector; Figure 10 (right) - exported 3D PDF

The ‘Intake interview module’ is included in the template layouts by default (Figure 8), and is represented by a green cube. Upon execution of the simulation the module adds property fields to components in the 3D environment, as instructed by the JSON file defined as source (e.g. the ‘Feeder’ component). After consulting with the client, the automation integrator places notes in appropriate fields (Figure 9). The module additionally ensures

that the notes are made available in the PDF, exported through the software's built-in export functionality. An example PDF export (Figure 10) can be found at [35].

5. User centric design and evaluation

The key of developing new applications is the early introduction of direct user feedback. It has been shown, that testing with a small number of participants several times can rapidly improve the design of an application [36]. This is why we tried to get as much end user feedback already during the development process and concluded it with a small study with end users.

5.1. Design process

In general, we followed the design process described in [37]. The described 'UX cycle' mainly consists of the steps analysis, design, prototype and evaluation, while the repeating of one step or jumping back to the last step is encouraged. We adjusted the process and the methods for our project setting.

The chronological steps are described in Figure 11. At first we developed the theoretical foundation of our framework (see aforementioned HRC Design Methodology) and undertook a profound contextual inquiry [37]. This lead to an early stage of the WST tool and was tested on the first application example, the bakery example. This real world example was used for several walkthrough iterations performed with external domain experts and lead to valuable qualitative findings, which have been mentioned above in the architecture. We adjusted the software in each step and undertook another round of walkthrough feedback.

As there are a lot of different application domains where our solution might apply useful, we chose another application example, the felt-tip pen box example. This was described with the theoretical approach (see Section 4) first. For the WST, we undertook a small user evaluation based on a formalized experimental design described later. We also used this example for walkthrough iterations later.

In the end we think that we achieved a preliminary design, which solves the requirements mentioned initially. The feedback of the various users was very helpful in achieving this goal. The qualitative findings have been directly included in the implementation of the tool. Nevertheless, we will further develop and evaluate the tool based on the same iterative process.

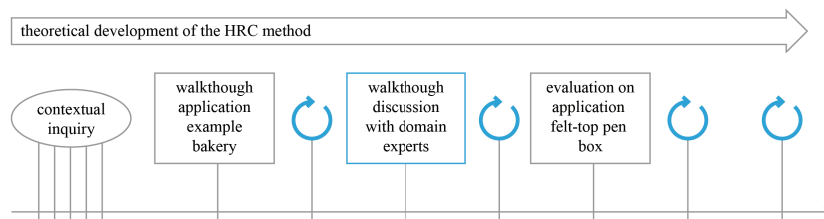


Figure 11 – WST design process

5.2. Evaluation procedure

As summarized in the previous section, the WST has been developed in collaboration with project partners and their wishes to validate its appropriateness for the group of users targeted by Factory in a Day.

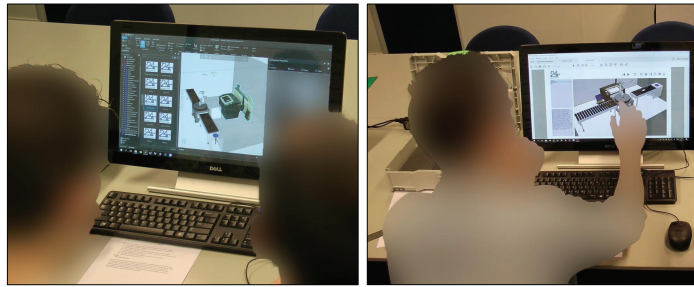


Figure 12 (left) - Importing and positioning of 3D scan in the layout; Figure 13 (right) - Interacting with the 3D PDF on a touchscreen

The use and performance of the tool was evaluated with four users. The participants completed the experiment in five steps;

1. Introduction of a typical (yet fictitious) automation problem (felt-tip pen box) by a video recording of a fictitious client.
2. 3D-scanning of a real-size mock-up of the machinery mentioned in the problem introduction.
3. Modelling and simulation of a solution to the problem using the WST.
4. Exporting the model as a 3D PDF.
5. Making adjustments and free-play with the WST and the 3D PDF.

The evaluation took place in an experimental setting equipped with video and audio recording devices. The users were guided through the experiment using instruction sheets and verbal instructions from the experimenters. After the experiments finished, each participant filled in a questionnaire and took part in a feedback session in which their responses were recorded.

The sessions took approximately 45 minutes per participant. All participants were able to start interacting with the tool with minimal explanation and demonstration. The experimenter's task was to let the participants execute the actions themselves yet to guide them towards the functions that they need to use inside the WST. This way they could focus on the problem that was introduced and the functionalities of the tool that were being investigated. Core functionalities of the tool such as drag-dropping of components, pan-rotate-zoom using a mouse and moving/rotating of parts using a Cartesian coordinate system were easily adopted by the participants including the participants that had less experience with CAD software.

5.3. Experimental setup and participants

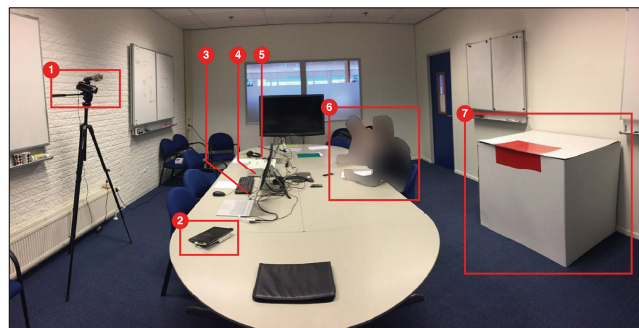


Figure 14 - Experiment setup

The experimental setup is depicted in Figure 14: On the left side (1) a camera for recording of participant's responses was installed. The tablet computer equipped with 3D scanning device was placed on the table (2), as well as the touchscreen computer running the WST (3) and a box containing the subject product of the experiment (4) and the computer for introducing the subject product and the automation problem to participants (5). An area on the table was reserved for feedback discussion and filling the questionnaires (6). A real size model of the machine that needs to be scanned by participants in the experiment was provided on the right (7).

All four participants had an engineering or design background and at least four years of professional experience, but were no roboticists. On average, they mentioned that felt 'fairly confident' in planning production lines. Even though 3 out of 4 participants had prior experience with 3D CAD software, none of them had experience with production planning or factory simulation applications. None of the participants had prior experience with 3D scanning.

5.4. Evaluation results

The participants were asked to fill in the QUESI [38] questionnaire which is used to assess the intuitiveness of the WST, specified in Figure 15. Questions Q4 and Q7 were graded the highest by the participants. These are indicators that the system was familiar in use and appropriate to solve the set assignment regarding modelling and simulating a simple production workflow.

However, the learnability of the tool is granted a neutral response by all participants (Q8, Q9, Q14), while two participants stated the system requires thinking about it, i.e. requires training (Q1, Q13). The current implementation of the WST consists of considerably more functionalities than what is needed for the core goals of the WST. This makes it look overwhelming to the novice user. A standard training of Visual Components currently takes three days to go through all features: modeling, simulation and programming. A basic training for the WST should be expected to take no longer than one day. Also, if completely novice users that have no experience in production planning are going to be trained, a training that introduces basic concepts of production and basic programming of robot manipulators should be developed.

question	P1	P2	P3	P4	Opinions between participants
1	2	3	4	1	I could use the system without thinking about it
2	4	4	4	3	I achieved what I wanted to achieve with the system
3	4	4	3	3	The way the system worked was immediately clear to me
4	4	4	5	4	I could interact with the system in a way that was familiar to me
5	2	4	3	5	No problems occurred when I used the system
6	3	3	4	4	The system was not complicated to use
7	5	4	4	3	I was able to achieve my goals in a way I had imagined to
8	2	3	3	3	The system was easy to use from the start
9	3	3	2	3	It was always clear to me what I had to do to use the system
10	2	4	4	3	The process of using the system went smoothly
11	3	4	2	4	I barely had to concentrate on using the system
12	4	4	3	3	The system helped me to completely achieve my goals
13	3	2	5	3	How the system is used was clear to me straight away
14	3	3	3	2	I automatically did the right thing to achieve my goals

Figure 15 - Quesi questionnaire results (1-Fully Disagree, 3-Neutral, 5-Fully Agree)

The participants generally regarded 3D scanning functionality to be an impressive feature of the tool. They believe that in many cases this will help speed up the process of modelling setups by helping to capture the location-specific details of a machine such as connecting pipes, ventilation and distances to its surroundings.

The participants mentioned strongly that the use of pre-set templates helps in the conceptualisation of the automated setup, especially in speeding up the process. This allows them to make a choice in the direction of the concept early on in the process. The ability to switch between robot manipulators from different manufacturers without needing to change the created setup was regarded as a valuable functionality.

The participants had a neutral stance towards the checklist functionality of the WST. They did mention that it as a nice-to-have functionality, yet did not see the real value in it as it was implemented in the current version for them as designers of the system. They mentioned that it should consist of a more concise set of questions in the design view. However it was mentioned that the exporting of answers to the 3D PDF is helpful in communicating with the client and mentioning setup-specific details that can otherwise remain unrecorded and might become forgotten/lost over time.

The participants regarded the 3D PDF functionality to be a valuable feature of the tool. They believe that this functionality is very essential in communicating the various design alternatives between the engineer and the client and that it takes many errors in communication away. Additionally, a single page 3D PDF is more valuable in some cases compared to a document with many pages trying to convey the same information.

5.5. Discussion

We wanted to test the appropriateness of the WST with the described iterative evaluation methods. As we are still developing the WST, this is a difficult task: The presented application based on small user group explorations cannot cater for the diverse applications in manufacturing. But they show already very promising results in the addressed test cases. Especially, the users approved the 3D scanning, the templates and the interactive 3D PDF, which are new contributions enabled by the architecture described in Section 3. Nevertheless, this evaluation doesn't substitute an comprehensive, statistically sound user test at the end of a product development.

6. Conclusions and future recommendations

In this work, we highlighted the need to support automation integrators in the initial stage of automation integration design projects, conceptualisation. We proposed to achieve this by lowering the threshold for modeling and simulation of an automated production line using a visual workflow modelling approach, the reuse of best-practice solutions and through facilitating shared libraries. Based on our forerunning Human-Robot Coproduction Methodology, a pilot version of a Workflow Simulation Tool (WST) was developed. This solution consolidates an off-the-shelf system for modelling and simulation (Visual Components) and 3D scanning (Structure Sensor) within a handheld portable system. The WST is intended to facilitate the discussion between the different stakeholders. Current version of the WST features the following functions:

- 3D scanning of the environment and specific machinery
- An online repository with automation templates
- Adaptable checklists of persistent notes to specify automation related complexity of tasks
- Export of workflow simulations in 3D PDF format, to be shared with stakeholders

The pilot implementation was iteratively developed and tested in close collaboration with automation integrators. The result offers an appropriate and fast modelling solution to reason on various scenarios of automated production lines, specifically with a richer dialogue on spatial aspects, which often comprise hidden requirements. This front-loading [39] prevents miscommunication and additional work in the automation process, and allows considering Human Robot Coproduction scenarios.

6.1. Recommendations for future implementation

The work presented in this paper is a first pilot implementation, we expect that the forerunning HRC framework will result in more defined interfaces to its peripheral notes (Augmented precedence diagram, HRC score card, deployment manual). The following improvements have been identified as priority:

- The checklist should be validated and revised by talking to more automation integrators.
- Optimize the information flow between 3D scanning application to Visual Components.

- An additional online module training course could to cover the WST context.

Other recommended improvements:

- Create an open repository of 3D scanned machinery and equipment where users can share their scan results with others. This would facilitate automation integrators and save them from performing redundant work.
- The level of realism of Visual Components implies a high level of solution fidelity while this might not be the case. It would be beneficial to use a cartoon/sketch 'shader' to show the 'underspecified character' of those early design proposals, as it is done in SketchUp[40] (3D design and visualisation software).
- An overview of the tasks/actions/workflow between components is not generated by Visual Components (nor the broader WST). It would be a helpful addition if this were developed and such visual process flow diagrams could be viewed. This could support other analyses, for example failure mode and effects analysis (FMEA).

7. Acknowledgements

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