

INDUSTRY 4.0: MASS PERSONALISATION THROUGH ONE-PIECE FLOW MANUFACTURING

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Abstract

Mass personalisation production has become the latest trend in the industrial production paradigm shift driven by Industry 4.0. Mass personalisation involves the co-creation of products to meet individual needs through the active participation of customers. Although the one-piece flow concept aligns well with the discrete nature of personalised production, its traditional applications under lean manufacturing are limited by the technological constraints in terms of systems integration and data flow that involve direct customer input. Industry 4.0 technologies such as cyber-physical systems, and Internet of Things offer potential solutions to break-through these barriers. To bridge these gaps, this paper presents a framework for the mass personalisation production through one-piece flow manufacturing integrated with Industry 4.0 technologies, guided by a well-known reference architecture model for Industry 4.0. The proposed framework is detailed in terms of integration and the mapping of the overall system to the considered reference model through an exemplary fruit juice production line. System integration and seamless data flow where customers can directly specify personalised product attributes are achieved using Industry 4.0 technologies. Performance analysis through simulation was conducted by comparing both mass production and mass personalisation production. The findings shows that while efficiency of mass personalisation slightly decreases due to personalisation complexity, the cycle time and throughput remain competitive, validating the feasibility of the proposed framework. This work highlights the novelty of extending one-piece flow beyond its lean manufacturing roots and demonstrates the realization of customer-driven personalisation through Industry 4.0.

Keywords: Industry 4.0; Mass personalisation; One-piece flow; RAMI 4.0

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Introduction

The recent business environment has been shifted into new market conditions due to the motivation of the technological advancements driven by Industry 4.0 (I4.0), especially the introduction of cyber-physical systems (CPS) and the Internet of Things (IoT) into manufacturing systems (Barata *et al.*, 2023; Anbesh *et al.*, 2025). This changed the industrial production paradigm from mass customisation to mass personalisation production (MPP) (Zhang & Ming, 2023; Nouhaila *et al.*, 2025), ensuring industrial competitiveness in the market. In other words, the focus of manufacturing production has moved from meeting the needs of market segments to satisfying each customer as an individual. I4.0 technologies are the central to this paradigm shift. They offer a smart and interconnected manufacturing environment via the integration of horizontal and vertical value chains, and leveraging the data analytics and information streams (Wang *et al.*, 2017a). With these capabilities, customers can actively participate in the product design process (Gu & Koren, 2022), significantly contributing to the realization of MPP.

Among the existing manufacturing models, the one-piece flow (OPF) model could be considered as the closest model to the concept of personalised production, even before the Fourth Industrial Revolution. Its main principle is to produce one unit of product at a time with no work-in-process, following lean manufacturing philosophy (Tang *et al.*, 2016; Ioana *et al.*, 2020). Theoretically, since only one product is processed at a time across all operations, customer participation at each stage becomes possible (Diaz-Reza *et al.*, 2022). This aligns closely with the idea of MPP. Yet, the implementation of MPP within the OPF systems remains a major challenge due to technological constraints, particularly in data information for personalised items (Wang *et al.*, 2017a). OPF manufacturing traditionally relied on human labours for repetitive tasks, which limited its application to standardised products. With the current Fourth Industrial Revolution and the rise of I4.0 enabling technologies, the potential to transform MPP is substantial. Automation and robotics could overcome dependence on manual labours while the horizontal and vertical integrations could ensure seamless communication between all stakeholders. These advancements make it increasingly feasible to realise MPP within the framework of OPF manufacturing.

Numerous studies on I4.0 have emerged since its introduction. Qin *et al.* (2016) identified the research gaps between the existing manufacturing

systems such as flexible and reconfigurable manufacturing system, and I4.0 requirement. They proposed a multi-layered implementation framework that relates the intelligence level to the automation level of the production system, laying the foundation for realizing I4.0. In addition, the work of Ilankovic *et al.* (2020) recorded the vital roles of I4.0 technologies which is the vertical and horizontal integration in establishing smart factories. These studies focus on the transformation of various manufacturing systems towards I4.0, but they do not specifically address MPP or OPF, which remain underexplored in the I4.0 context.

The unique highlight of this study is the integration of three key systems: I4.0, MPP, and OPF manufacturing, to form a production system to meet the customer-oriented trend of manufacturing. Previous research has typically examined these systems in isolation. In the case of OPF, existing studies often relate it to lean manufacturing and its applications (Ioana *et al.*, 2020; Diaz-Reza *et al.*, 2022). This work aims to bridge the gap by developing a practical OPF manufacturing line for MPP that complies with the Reference Architecture Model of I4.0. By embedding I4.0 enabling technologies within the OPF manufacturing using a proper reference model, it offers an appropriate platform for personalisation and flexibility in producing items with diverse requirements.

Mass Personalisation Production

MPP is an evolution of mass customisation production (MCP) and mass production (MP) and is regarded as the latest production paradigm in industries, driven primarily by customer desire. The main objective of personalisation is to fulfil the desire and requirement of each customer as an individual rather than a market segment (Kabasakal *et al.*, 2017). In MCP, product variations are achieved through modular design on a common production platform within a product family (Zhang & Ming, 2023). Customers make changes based on a set of known modules, components or subsystems, and ultimately receive similar customised products within the family. Hence, customer involvement in MCP is limited (Wang *et al.*, 2017a). On the other hand, MPP requires production to be highly flexible, configurable and changeable as the end product is able to be differentiated at the parameter or module level to meet the unique requirements of customers. The essence of MPP lies in the co-creation of products

where customers are actively involved in production processes (Kumar, 2007; Zhang & Ming, 2023). This active participation enables the creation of personalised products that satisfy the unique requirements of each customer.

Tseng *et al.* (2010) highlighted three main factors in the MPP ecosystem, namely; core infrastructure including the technical architecture and business model, hard components that meet the physical functional requirements of personalisation, and soft characteristics that focus on customer experience and human-product interaction. However, realizing MPP is challenging as it requires a higher level of customer involvement and information flow compared to MCP. To address this issue, Wang *et al.* (2017a) proposed an I4.0-based framework for MPP. It consists of six elements: network layer, Internet of Services, cyber-physical system, manufacturing execution system, enterprise information system, and warehouse management system. Customers are integrated into the product design process through the Internet of Services, supported by a stable networking system. This elevates customer involvement and ensures a stable information flow for both operational and strategic business decision-making. Torn & Vaneker (2019) suggested a conceptual horizontal integration through a collaborative network between companies. This allows companies to share resources and reduce the burden of equipment capacity and financial constraints when handling product variety. Although these works relate I4.0 to MPP, their proposed strategies remain mostly at a conceptual level or are limited to case-specific contexts with no common framework. A common framework is vital to create mutual understanding among stakeholders and enable consistent application of I4.0 in MPP.

Reference Architecture Model for I4.0

One of the most significant frameworks reported in the context of I4.0 research is the Reference Architecture Model for I4.0 (RAMI 4.0). This model incorporates all the essential aspects of I4.0 into a three-dimensional layered model, and defines horizontal and vertical integration and product life cycle engineering (Reference Architecture Model Industry 4.0 (RAMI 4.0), 2016). It serves as a guideline for implementing I4.0. Further details are provided by Adolphs *et al.* (2015). In general, RAMI 4.0 consists of three axes:

1. The Architecture Layers axis comprises six layers that are used to describe the information technology representation of a complex process or system by decomposing it into structured layers.

These include Asset, Integration, Communication, Information, Functional, and Business layers.

2. The Life Cycle and Value Stream axis represents the lifetime of a product or asset and its value-added process, based on the IEC 62890 standard. It is divided into “Type” and “Instance” which refer respectively to the stage of designing and prototyping, and the stage of producing the actual product.

3. The Hierarchy Levels axis represents the functionalities of different components involved in integrating enterprise and control systems within a facility or system, based on the IEC 62264 and 61512 standards. This axis consists of seven levels from the lowest level of Product, Field Device, Control Device, Station, Work Centres, and Enterprise, to the highest level of Connected World.

The introduction of RAMI 4.0 standardised I4.0 implementation as many studies have emerged since then. Wang *et al.* (2017b) proposed a topological approach for mapping the technologies to relevant layers of RAMI 4.0 for the ease of I4.0 implementation. Febriani *et al.* (2020) provided a practical guide for developing a smart welding station system compliant with RAMI 4.0 while Brencher *et al.* (2021) suggested a production development path for evolving production processes towards I4.0 by referencing RAMI 4.0. Also, Baptista and Barata (2021) integrated an enterprise architecture into RAMI 4.0 in their digital transformation pilot projects. These exemplary studies offer valuable insights into the application of RAMI 4.0 and further motivate its potential for use in MPP and OPF manufacturing systems.

Proposed Framework of OPF Manufacturing for MPP

Based on RAMI 4.0, the framework of OPF manufacturing for MPP is proposed to satisfy individual requirements of customers by providing distinct products. The emerging technologies in I4.0 such as IoTs, CPSs and communication services are integrated into the proposed framework. Figure 1 displays the overall proposed framework of OPF manufacturing for MPP according to RAMI 4.0. The main focus of this framework is on the Architecture Layers and Hierarchy Levels axes of RAMI 4.0. Only the production instance is considered for the life cycle and value stream axis as no development and maintenance are involved in this work (refer to the highlighted red cuboid region in Figure 1). For the layers axis, the proposed framework spans from the Asset layer, including the physical machines, equipment, actuators,

and sensors, through the Integration and Communication layers that enable interoperability via I4.0 communication protocol, up to the Information and Functional layers that define data models and control logic. The framework connects directly to mass personalisation as the core driver at the Business layer. In the Hierarchy Levels axis, the proposed framework covers all levels, from the personalised product, sensors, and controllers, up to the online ordering system that enable the active participation of customers. The framework mainly addresses the Instance phase of production as mass personalisation requires the continuous adaptation of production parameters for each personalised product. By clearly positioning the proposed framework into this red cuboid region, this work demonstrates compliance with RAMI 4.0 while outlining the scope of implementation. Figure 2 presents the details of architecture layers against hierarchy levels.

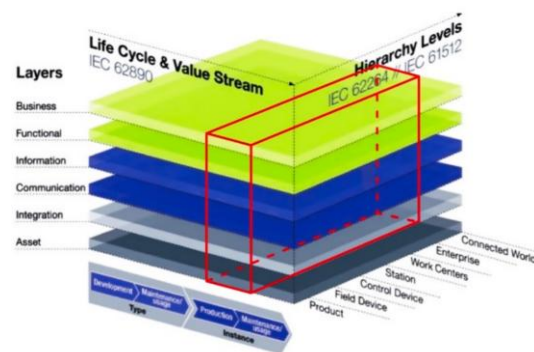


Figure 1. The proposed framework of OPF manufacturing for MPP based on RAMI 4.0 (red cuboid region)

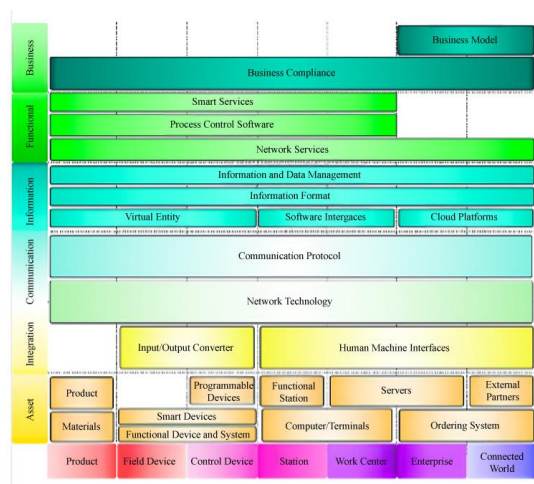


Figure 2. Overall proposed framework of OPF manufacturing for MPP

Asset Layer

The Asset layer comprises the physical machines or devices that exist and their respective connection to virtual representation in the higher layers. These assets include all physical devices from the Product level to the Connected World level: raw materials and products, programmable devices, smart devices, functional devices and systems, functional stations, computers, servers, ordering systems, and external partners.

Integration Layer

The Integration layer is the transition layer between the Asset and Information layers. It contains the components with properties or functions that allow the event that occurred in the physical world to trigger the event in the virtual world. The hardware and software interfaces required to link various systems and devices are included in this layer. Examples of these components include input-output converters, which are used at the Field Device level and human-machine interfaces that are normally found at the stations or work centres.

Communication Layer

The Communication layer consists of standardised I4.0 compliant communication protocol that use a common format to ensure communication is established across different layers and levels. In addition, network technology and infrastructure span both the Integration and Communication layers to ensure successful linkage between the physical and the virtual world for the establishment of CPSs.

Information Layer

In the Information layer, all different data needed to support the operations of the organisation or process are integrated consistently. Data sources, data storage, and data processing are included in this layer. Examples of components include virtual entities, software interfaces, and Cloud platforms with proper information and data management systems.

Functional Layer

The Functional layer incorporates the formal and digital description of respective roles and technical functions or services provided by different assets. Examples are smart services from field devices, process control software or systems such as manufacturing execution systems and enterprise resource planning systems, and network services that allow the access of information.

Business Layer

This top layer of the axis describes the business procedures and goals of an organisation including overarching business strategies and objectives, as well as legal and regulatory standards such as safety operation standards. This layer also represents the organisation's business model and ensures organisation business compliance.

Comparison of Production Frameworks

Before presenting the implementation example, the proposed framework is briefly compared with existing common production frameworks to highlight its expected benefits and trade-offs. The conventional MP represents the baseline model for high volume, standardised products, while the traditional OPF framework focuses on reduced work-in-progress (WIP) and shorter lead times but typically lacks digital integration. Existing mass personalisation frameworks extend customisation capabilities, yet they do not fully leverage I4.0 interoperability

models and retain batch characteristics. The proposed framework integrates the OPF concept with I4.0 standards - including RAMI 4.0 mapping, and I4.0 communication protocols - to enable traceable and scalable mass personalisation on a single unit flow basis. Table 1 summarises the comparison of production frameworks for conventional MP, traditional OPF, existing mass personalisation, and the proposed framework for MPP.

Implementation Example

An OPF production line for MPP based on RAMI 4.0 was set up at a higher learning institution in Malaysia, as shown in Figure 3. Fruit juice is produced on this line to demonstrate the MPP based on the proposed framework. Figure 4 displays the respective stations in the OPF production line for MPP.

Table 1. Comparison of production frameworks for conventional MP, traditional OPF, existing mass personalisation, and the proposed framework for MPP

Frameworks	Advantages	Limitations
MP (Wang <i>et al.</i> , 2017a)	- High throughput and economies of scale for standardised products. - Mature and stable.	- Inflexible for customisation or personalisation. - Long changeover times and high WIP when customisation or personalisation is required.
OPF (Ioana <i>et al.</i> , 2020)	- Able to reduce WIP and production lead time. - Improves flow efficiency and quality at the shop floor. - Typically faster response than batch systems.	- Limited digital and information technology integration. - Limited traceability. - Limited high-mix personalisation due to limited information and data flow system.
Existing mass personalisation (Aheleroff <i>et al.</i> , 2021)	- Allows for personalisation of production through information technology tools. - Improves market responsiveness.	- Scheduling complexity. - Higher operational cost. - Lack of adherence to I4.0 standards.
Proposed framework	- Enables single unit personalisation. - Enhance traceability and interoperability. - Mapping to RAMI 4.0 ensures standard-compliant and scalable implementation.	- Requires higher initial investment for the I4.0 infrastructure. - Requires retraining of staff for I4.0 systems and protocols.



Figure 3. The overall OPF production line for MPP

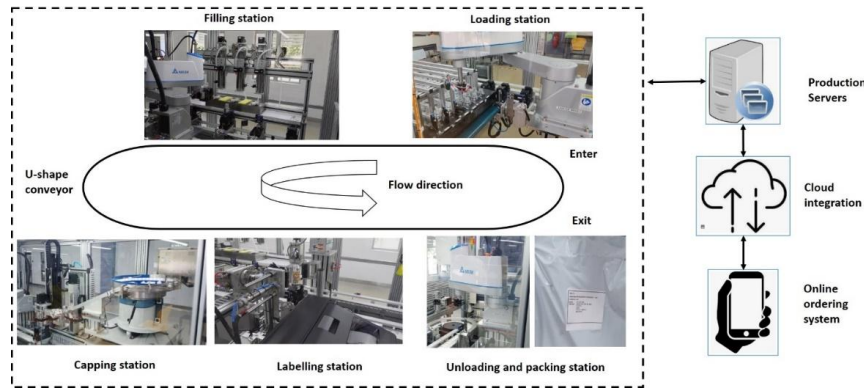


Figure 4. The respective station in the OPF production line for MPP

Table 2. List of core components used for the development of the production line for MPP

No.	Items	Quantity	Brand/Supplier
1	Flexlink conveyor	1	Flexlink
2	Color label printer	1	Epson
3	B3 servo motor 400W 3000rpm	1	Delta
4	B3 series servo Drive	1	Delta
5	ES2 series PLC main unit (relay)	1	Delta
6	M series inverter	1	Delta
7	B3 ethercat servo driver 400W	2	Delta
8	LU actuator C/W 400W servo motor	2	Delta
9	B3 ethercat servo driver 100W	3	Delta
10	B3 servo motor 100W	3	Delta
11	SCARA robot teach pendant	1	Delta
12	SCARA robot (Arm length: 600mm;Max payload: 6kg; z-axis stroke: 200mm)	3	Delta
13	SCARA robot (Arm length: 400mm; Max payload: 3kg; z-axis stroke: 150mm)	1	Delta
14	Pavoni sistemi products	3	Sciengate
15	Tag disk dia. 30 2K bytes feram	4	Schneider
16	Schneider smart antenna	7	Schneider
17	Nema 23 stepper motor	3	Moon
18	Nema 11 stepper motor	1	Moon
19	STF series fieldbus control DC stepper drives	4	Moon
20	PLC CPU	6	Advantech
21	Touch monitor	6	Advantech
22	SCADA system	1	Advantech
23	Jih water pump	3	China
24	Hiwin actuator	3	Hiwin
25	Auto bagger packing machine	1	Gurki
26	Cylinders (various types)	22	SMC Automation

The developed production line consists of five stations: loading station, filling station, capping station, labelling station, and unloading and packing station. All the stations are equipped with a Radio Frequency Identification (RFID) module that enables the reading from and writing to the RFID tag of each product. The materials transferring system used is a U-shape conveyor, the typical setup for the OPF manufacturing environment. This configuration supports discrete production of personalised products from each customer. The selective compliance assembly robot (SCARA) is used to transfer the juice bottles from stations to the U-shape conveyor and vice-versa. Through the IoTs, an online ordering system is used to facilitate active involvement of customers through their order

and personalisation of their product specifications. Personalisation can be performed on the volume of fruit juice and the proportion of each fruit in a blend, depending on individual preferences of taste, cost, and nutrition. Moreover, customers can upload custom images and personal messages to be printed on fruit juice bottles to satisfy their unique individual requirements. Customers are also able to choose either pick-up or delivery for their end product and can input their delivery information if the delivery option is chosen. Table 2 tabulates the list of core components used for the development of the production line, while Table 3 presents the dedicated core components and technologies used for each station.

Table 3. Core components and technologies for each station of the developed production line

Stations	Functions	Core Components and Technologies
Loading	- Feed empty bottles into line based on customer orders. - Write personalised order information to RFID tag. - Placement of bottle on pallets.	- Conveyor system with photoelectric and proximity sensors. - SCARA robotic arm with pneumatic gripper. - Pallet handling with stopper mechanism. - Supervisory Control and Data Acquisition (SCADA) master server and industrial personal computer (IPC) for control and data processing. - RFID read/write system.
Filling	- Read order information including fruit juice composition and volume from the RFID tag. - Dispense personalised liquid volumes (up to three different liquid ingredients) into bottle.	- RFID module for order retrieval. - SCARA robotic arm for pick/place and positioning of bottles. - Liquid dispensing system with pumps, nozzles and tanks. - Load cell for volume measurement. - IPC controller module for process control.
Capping	- Feed, orient, and apply bottle caps. - Secure caps onto filled bottles.	- Vibratory bowl feeder. - Caps screwing module including linear actuator and motor. - RFID module for process update.
Labelling	Print and apply personalised labels including nutrition tables, text, and images.	- Industrial printer. - SCARA robotic arm with suction gripper. - Rubber roller for even label attachment.
Unloading and Packing	- Unload and pack finished products. - Print and attach shipping information.	- RFID module for recipient information. - SCARA robotic arm for packing. - Bag feeding and sealing system. - Printing machine for labels.

The first station is the bottle loading station. Based on the customer's order and personalisation through the online ordering system, information such as volume (size), fruit juice composition, messages, photos and delivery address is stored in an RFID tag. The bottle size, as decided by the customer, is transferred by the SCARA robot to the corresponding jig and onto the conveyor, proceeding to the filling station. At the filling station, the RFID module reads the personalised fruit juice composition from the RFID tag and fills the bottle accordingly. The capping station caps the bottle based on the size, as specified in the RFID tag, before transferring it to the labelling station. Personalised labels - including personalised messages, photos and nutrition facts calculated from the juice composition are printed and attached to the corresponding bottle. Lastly, the SCARA robot transfers the completed product for packing and the delivery information is printed and attached to the package. Throughout the production stage, the product is tracked via RFID read and write modules.

The components of the developed production line are mapped to each aspect of RAMI 4.0:

1. Asset layer - This layer includes all physical assets: raw materials and products, programmable and smart devices, functional devices, and systems, computers, servers, and ordering systems.

2. Integration layer - Standard interfaces and protocols are created here for data exchange between various layers and components. Passive RFID communication is employed for product tracking. Serial communication is used to integrate

Programmable Logic Controllers (PLCs) with other electronic devices.

3. Communication layer - four main communication protocols are employed to transmit information between different levels of the hierarchy: (a) the hypertext transfer protocol (HTTP) to connect customers to the online ordering system and Cloud Services, (b) CODESYS Open Platform Communication Unified Architecture (OPC UA) for secure data exchange (Ye *et al.*, 2022) between Supervisory Control and Data Acquisition (SCADA) Master servers and RFID systems; (c) RFID for product identification and tracking (Mostaccio *et al.*, 2023); and (d) Modbus for communication between different electronic devices, actuators and PLCs.

4. Information layer - The personalised input data from customers are stored in the Cloud. The data is accessible and transferable to the SCADA Master servers and is further extended to human-machine interfaces and RFID tags. In addition, the information for each station is continuously updated in correspondence to the data extracted from the RFID tags for personalised production.

5. Functional layer - There are three main elements in this layer: input functions, production functions, and output functions. Input functions involve the personalised data input from customers through the online ordering system. Based on this information, the production functions are then triggered to execute manufacturing process at all five stations, controlled by the respective controllers, to produce the personalised product. The output functions involve producing the final

product according to the personalised specifications stored in the RFID tags.

6. Business layer - The customer is positioned at the Connected World level as the initiator of personalised production. The online ordering system at the Enterprise level aids the business in facilitating the automatic processing of personalised orders from customers. These orders then triggered the production at the shop floor, cascading from the work centre down to the product levels. The

personalised fruit juice is created at the conclusion of the procedure, which is the final business output.

Table 4 summarises the mapping between the considered aspects and components in the developed production line. In addition, Figure 5 presents the network topology of the developed production line. The samples of OPC UA nodes, PLC programming, RFID memory map, and data schema are extracted and presented in Figure 6, Figure 7, Figure 8 and Figure 9, respectively.

Table 4. Mapping between the considered aspects of the proposed framework (refer to Figure 2) and components in the developed fruit juice production line

Layer	Aspects	Components in the Developed Line
Asset	Product	Personalized fruit juice
	Materials	Bottles and ingredients
	Functional devices and system	SCARA robots
	Smart devices	Sensors and actuators
	Programmable devices	PLCs
	Functional station	All five stations
	Computer/terminals	Personal computers
	Servers	Database and web servers
	Ordering system	Online ordering portals
	External partners	System integrators and vendors
Integration and Communication	Input/output converters	Analogue and digital converters
	Human-machine interfaces	Interactive control panels
	Network technology	Ethernet and wireless network
	Communication protocol	OPC UA and Modbus
Information	Virtual entity	Simulation model
	Software interfaces	DBeaver
	Cloud platform	Online ordering system
	Information and data management	Data storage and security management
Functional	Network services	Data transmission and synchronization, network management
	Process control software	SCADA system
	Smart services	Asset tracking and optimization
Business	Business compliance and model	Regulatory compliance and standards

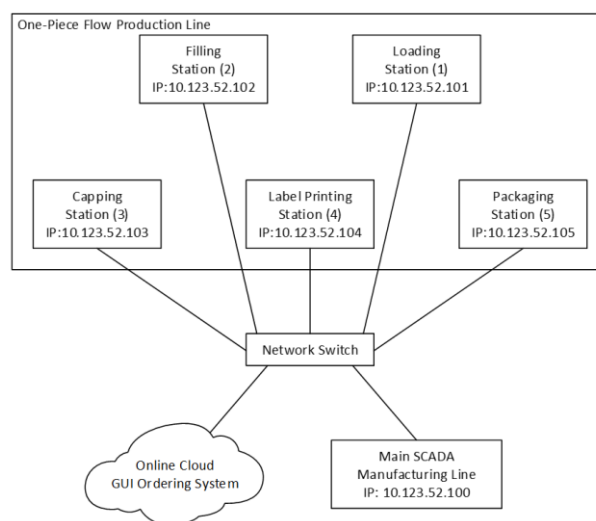


Figure 5. Network topology of the developed production line

Default OA View				
Server	Node id	Display Name	Value	Datatype
Station 1	NS4(String var Advantech (x86_64-RTE) SM.Application.SCADA.WO_DATA.BOTTLE	BOTTLE	330	UInt16
Station 1	NS4(String var Advantech (x86_64-RTE) SM.Application.SCADA.WO_DATA.COLLECTION	COLLECTION	sef	String
Station 1	NS4(String var Advantech (x86_64-RTE) SM.Application.SCADA.WO_DATA.CUST_ADDR1	CUST_ADDR1	JALAN GENTING KELANG	String
Station 1	NS4(String var Advantech (x86_64-RTE) SM.Application.SCADA.WO_DATA.CUST_ADDR2	CUST_ADDR2	SETAPAK	String
Station 1	NS4(String var Advantech (x86_64-RTE) SM.Application.SCADA.WO_DATA.CUST_ADDR3A	CUST_ADDR3A	53300	String
Station 1	NS4(String var Advantech (x86_64-RTE) SM.Application.SCADA.WO_DATA.CUST_ADDR3B	CUST_ADDR3B	KUALA LUMPUR	String
Station 1	NS4(String var Advantech (x86_64-RTE) SM.Application.SCADA.WO_DATA.CUST_ADDR4	CUST_ADDR4	MALAYSIA	String
Station 1	NS4(String var Advantech (x86_64-RTE) SM.Application.SCADA.WO_DATA.CUST_NAME	CUST_NAME	JIA JAN ONG	String
Station 1	NS4(String var Advantech (x86_64-RTE) SM.Application.SCADA.WO_DATA.INGR1_DEN	INGR1_DEN	1	Double
Station 1	NS4(String var Advantech (x86_64-RTE) SM.Application.SCADA.WO_DATA.INGR1_VOL	INGR1_VOL	110	Double
Station 1	NS4(String var Advantech (x86_64-RTE) SM.Application.SCADA.WO_DATA.INGR2_DEN	INGR2_DEN	1	Double
Station 1	NS4(String var Advantech (x86_64-RTE) SM.Application.SCADA.WO_DATA.INGR2_VOL	INGR2_VOL	110	Double
Station 1	NS4(String var Advantech (x86_64-RTE) SM.Application.SCADA.WO_DATA.INGR3_DEN	INGR3_DEN	1	Double
Station 1	NS4(String var Advantech (x86_64-RTE) SM.Application.SCADA.WO_DATA.INGR3_VOL	INGR3_VOL	110	Double
Station 1	NS4(String var Advantech (x86_64-RTE) SM.Application.SCADA.WO_DATA.SO_ID	SO_ID	68899229be732b09ecdee072	String
Station 1	NS4(String var Advantech (x86_64-RTE) SM.Application.SCADA.WO_DATA.SO_PRODID	SO_PRODID	68899229be732b09ecdee074	String
Station 1	NS4(String var Advantech (x86_64-RTE) SM.Application.SCADA.WO_DATA.SO_SUBID	SO_SUBID	1234	Int16
Station 1	NS4(String var Advantech (x86_64-RTE) SM.Application.SCADA.WO_DATA.WO_ID	WO_ID	68899229be732b09ecdee0721	String
Station 1	NS4(String var Advantech (x86_64-RTE) SM.Application.SCADA.WO_DATA.WO_SUBID	WO_SUBID	100	Int16

Figure 4. The extracted sample of OPC UA nodes using UaExpert software

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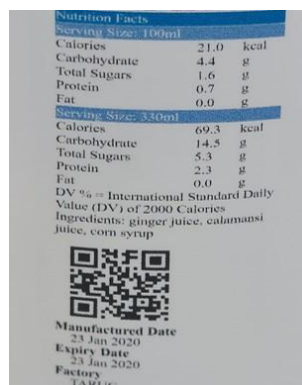
1  PROGRAM POU_SEQ_LOAD
2  VAR
3      Initialized : BOOL;
4      Station_State : INT;
5      Station_Work_Done : BOOL;
6      INDEX:INT;
7      last_Tail_Lane : INT;
8      last_Short_Lane : INT;
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Figure 9. The extracted sample of data schema



(a)



(b)

Figure 10. Examples of (a) end products with personalised images, and (b) the nutrition facts based on personalised proportion of the fruit juice and sizing in a blend

Figure 10 shows examples of the personalised end product from the developed manufacturing line. In this developed production line, personalisation is realised through the active participation of individual customer in the online ordering system. Based on the proposed framework, the personalised fruit juice is produced effectively.

Performance Analysis for the Implementation Example

A simulation model was developed based on the time study data collected from the developed production line for performance analysis. A total of 72 products were produced on the production line and the time required for each process was recorded. The simulation model was validated by comparing the mean production time of the actual line with the model using analysis of variance (ANOVA). The ANOVA results indicated no statistically significant difference between the two means. Thus, the simulation model can reliably represent the actual production line.

Two production scenarios were simulated: (a) MP, and (b) MPP. In the MP scenario, bottles (units) were fed into the line at a constant rate with fixed parameters to simulate continuous production. In contrast, in the MPP scenario, each bottle entered the line with a random composition and volume. A total of 350 bottles of fruit juices were produced in each scenario. The two scenarios are summarised in Table 5.

Table 5. Setup of each scenario in simulation

Scenario	Parameters	Personalisation
MP	Constant	No
MPP	Random	Yes

In this work, the MP is chosen as the baseline for comparison. The main contribution of this study is to demonstrate how I4.0 enables mass personalisation by integrating OPF with I4.0 technologies. Since MPP is conceptually positioned as the evolution of MP where standardised high-volume production is transformed into flexible customer-oriented production, MP provides the most relevant benchmark to highlight the shift from standardisation to personalisation. In addition, traditional OPF is mainly associated with lean manufacturing practices (Ioana *et al.*, 2020) which aim for efficiency in repetitive and low variation contexts. It was not originally designed for personalisation. Therefore, benchmarking against traditional OPF does not effectively demonstrate

the contribution of I4.0 to personalisation at scale. Table 6 tabulates the results obtained for each scenario. The cycle time (*CT*), throughput (*TP*), performance (*P*), and error rate (*ER*) were calculated using equations (1), (2), (3), and (4) (Agustiady & Cudney, 2023).

$$CT = \frac{\text{net run time}}{\text{number of produced unit}}, \quad (1)$$

$$TP = \frac{\text{number of produced unit}}{\text{total production time}}, \quad (2)$$

$$P = \frac{\text{number of produced unit}}{\text{net run time} \times \text{ideal run rate}} \times 100, \quad (3)$$

$$ER = \frac{\text{number of defects}}{\text{number of produced unit}} \times 100. \quad (4)$$

Table 6. Performances of each simulated scenario

Performance	MP	MPP
Total produced units	350	350
Total defects	82	89
Total production time (mins), (a)	550.21	491.94
Total downtime (mins), (b)	157.49	130.11
Net run time (mins), (a-b)	392.72	361.83
Ideal run rate (unit/mins)	1.09	1.27
Cycle time (mins/unit)	1.12	1.03
Throughput (unit/mins)	0.64	0.71
Error rate (%)	23.4	25.4
Performance (%)	81.8	76.2

The performances of MP and MPP were compared in terms of cycle time, throughput, error rate and performance percentage. For cycle time and throughput, both MP and MPP presented comparable results. This indicates that the integration of I4.0 technologies successfully minimises the delays and process variability typically associated with personalisation. The findings also highlight that I4.0 technologies enable MPP to remain competitive in throughput, even providing personalisation. On the other hand, MPP presents a higher risk of errors compared to MP due to product variability. The findings also indicate that the performance of MPP is lower than MP by 5.6%. This outcome is expected as MP benefits from standardised production parameters. In contrast, mass personalisation introduces product diversity, which inherently reduces performance. Nevertheless, the slight trade-off in performance of MPP should be interpreted in the broader context of I4.0 manufacturing objectives. The integration of I4.0 technologies using proper architecture enables flexibility and customer-oriented production. This could enhance responsiveness to market demands. Furthermore, it also delivers added value in terms

of adaptability and personalisation. Overall, the production line successfully integrates OPF manufacturing, MPP and I4.0 in accordance with RAMI 4.0. It also demonstrates that I4.0 technologies such as IoT, communication services, and CPS, are able to overcome the data flow barriers found in the traditional OPF manufacturing system to realise MPP. The functional feasibility of the proposed framework has been proven through this implementation.

Conclusions and Future Works

In this work, a framework that integrates OPF manufacturing, MPP, and I4.0 has been proposed to overcome the barriers of traditional OPF manufacturing for mass personalisation by integrating customer inputs in defining product specification using I4.0 technologies. An exemplary implementation in personalised fruit juice production is detailed to demonstrate the feasibility and practical applicability of the proposed framework. Overall, the results show that MPP can be achieved based on the proposed framework with only a slight trade-off in performance. However, it is able to enhance responsiveness to market demand and improve competitive advantage. Moreover, this study establishes a baseline measurement of the performance gap between MP and MPP. Future research may dive into advanced scheduling strategies and artificial intelligence-based optimisation to minimise this gap and enhance the scalability of MPP without compromising efficiency.

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