Development of a Cost-Effective Cyber-Physical Production System for the Make-to-Order Industry

Anas Ma'ruf, Rifqi Qinthara and Muhammad Rafif Rajendra Wiradikara
Faculty of Industrial Technology
Bandung Institute of Technology
Bandung, 40132, Indonesia
maruf@itb.ac.id, rifqiqinthara@gmail.com, rafifrajendra123@gmail.com

Abstract

This paper identifies the necessity of a Cyber-Physical Production System development for the Make-to-Order industry. The uniqueness of the Make-to-Order industry is that orders are low in production volume but wide in product variety. Thus, accurate and real-time data acquisition of the production activity is necessary to support decision-making to respond to customer orders and monitor production activities. The proposed Cyber-Physical Production System utilizes RFID and current sensors to identify the parts and machine activities. The Cyber-Physical Production System is proven cost-effective to the alternative controller-based Cyber-Physical Production System. Initial implementation has proven a viable solution and provides benefits to support decision-making in the Make-to-Order industry.

Keywords
Cyber-Physical Production System, Internet of Things, Make-to-Order, Production Activity Control.

1. Introduction
One of the manufacturing strategies to respond to customer requirements is make-to-order (MTO). The MTO industry has the production capacity to create a product based on the specifications desired by customers. The key to responding to customers lies in the production capabilities in manufacturing the order specification and the ability to track the production progress. Therefore, records of production activities are essential due to the wide variety of products with low production volumes. The recording of production activities in the MTO industry needs to be carried out on every order and at every production facility. It differs from the mass production industry, in which production activities can be monitored at the last stage of the production process or at a bottleneck machine.

This research focuses on the MTO industry, which produces various discrete products. The machines used in manufacturing the products consist of multiple CNC machines and conventional machines having various manufacturing processes such as milling, turning, drilling, grinding, etc. Production activities are generally recorded in the form of a logbook. The logbook contains entries of operator activities in processing customer orders following the process plan (machine sequence) for each order. The operator will regularly update the production status in the logbook. The profiling of the logbook data is then used for monitoring and evaluating the production activities by connecting the logbook to a production planning system, such as enterprise resource planning (ERP). The ERP system is the basis of information used in decision-making to increase capability, adaptability, and awareness in production activities (Urbina Coronado, 2018).

Based on a survey of several MTO industries, logbook filling is performed manually through operator entry or barcode scan. This is in line with the findings of Seegar (2022), who stated that there are numerous missing links between physical systems (machinery and equipment) and production decision-making systems. This manual process presents various drawbacks, namely inaccuracies in production data and additional administrative burdens to operators. On the other hand, production activity logbooks are a source of increased responsiveness to customers and productivity (Mudgal et al., 2020). The development of production logbooks in the MTO industry has the potential to utilize Industry 4.0 technology. One of the pillar technologies of Industry 4.0 is the Cyber-Physical Production System (CPPS). CPPS allows various production objects to be interconnected through Internet of Things (IoT) devices. In the case of the MTO industry, there are two critical production objects: customer order and machine for processing the orders. Customer order monitoring is carried out to track the progress of an order, while machine monitoring is conducted to track the capacity (load) of the production facility. Thus, interconnecting between customer orders and machines will serve as a basis for the digital transformation of the MTO industry.

1.1 Objectives
This study aims to develop a cost-effective CPPS for the MTO industry. Development cost is an indicator since the MTO industry already has various production facilities but still needs to be digitally connected. In addition, the monitoring of production activities needs to be carried out in detail for each order and at each stage of the machining process so that the number of CPPS required in an MTO company follows the number of orders and the number of machines available in the industry. The development of CPPS is expected to form the foundation for automatic data acquisition. These data are essential for scheduling, dispatching, and production activity control.

2. Literature Review
The development of CPPS is increasing along with the progress of the fourth industrial revolution (Danelon Lopes and Neumann, 2021). CPPS is a combination of manufacturing system technology consisting of physical and virtual systems that are autonomous and interconnected in carrying out production activities. According to Rojas (2019) and Moghaddam (2018), IoT is the key to connectivity, enabling integration and interoperability between CPPS elements. Connectivity allows hardware activities to be recorded, enabling an analysis of decisions related to production activities.

The standard data collection method of a CPPS uses controllers or sensors (Lee et al., 2015). Data retrieval via controllers is a relatively new approach. Hence the equipment that supports communication through controllers is widely available on new devices. An example of a standard controller in data retrieval applications is MTConnect. By using the MTConnect protocol, various production equipment can perform data communication and mining (MTConnect Institute, 2022). Currently, controllers with the MTConnect feature are available in an optional form. The additional cost required for adding this feature is approximately USD 1,000, which needs to be considered (Shop Floor Integration, n.d.). An alternative approach to data acquisition is to use various sensors according to the requirements, such as cutting force, vibration, emission, temperature, etc., and subsequently send the data through a manufacturing execution system (Wauters et al., 2012). In addition to these sensors, radio frequency identification (RFID) is widely used to monitor production activities (Altaf et al., 2018; Qian et al., 2023; Zhong, 2019). This research is focused on using sensors, assuming the MTO industry already has production facilities. In this research, the investment cost is considered a practical constraint due to the fluctuation of CPPS needs associated with the number of customer orders and machines required to process the orders in the MTO industry.

CPPS and its application in the industry have been carried out for various purposes. Grosch (2022) implemented CPPS for the energy-flexible operation of production machines. CPPS consists of simulation models to predict and control production machines to operate in an energy-flexible manner. Iannino (2022) proposed a CPPS modular architectural system for the steelworks industry that produces long products such as rails and tubes. The application-oriented of proposed architecture has been tested from an industrial perspective by investigating and exploiting an agent-based technology solution. Kumar (2021) developed a CPPS-based 3D printing process decision-making system that allows users to assess their carbon footprint by monitoring energy and material usage. Among all CPPS applications, IoT is the primary integrator that connects physical elements and decision-making systems (Zhang, et al., 2018). This research will focus on the MTO industry having a discrete production process. The complexity of production that arises due to the different machining sequences for each product makes it essential to monitor production activities in real-time. IoT will be an integrator between various physical elements of production and decision-making systems.

3. Methods
This research is conducted as a case study by mapping the as-is and to-be systems, consisting of requirement statements and functional requirements of a CPPS for the MTO industry. The subsequent step is analyzing the gap between the as-is and to-be systems. A gap analysis is carried out to produce a CPPS framework for monitoring production activities in the MTO industry. The third stage of the research is to determine the CPPS design requirements and architecture.

3.1 As-Is System

Figure 1 shows the configuration of the as-is system in the studied MTO company. Production monitoring activities were carried out with a logbook filled in manually by operators following the progress of production time. The data being logged by the operator consists of which order is being processed at which machine at what time. The data logged will linearly proliferate to the number of orders and machines used to process a part order. The logbook data is further digitalized and stored in an Enterprise Resource Planning (ERP) system, which can be viewed and used by the Production Planning and Inventory Control (PPIC) department. The PPIC evaluates the deviation between the production plan and actual production progress. If deviation arises to a certain point, PPIC will take action in various forms, such as re-route product routing to an alternative machine, overtime scheduling, rescheduling the production plan, or other viable action to keep track of customer requirements.

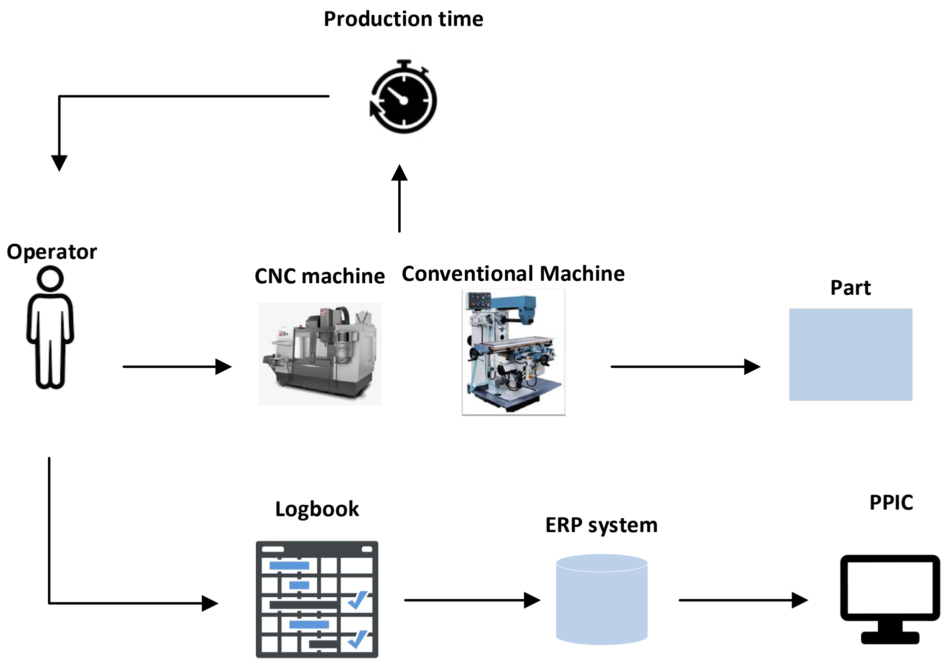

Figure 1. As-is system configuration

3.2 To-Be System Requirements

The requirements for a to-be system were defined based on the problems discovered in the MTO industry. The statements were obtained through group discussions with several MTO industry practitioners. There are two requirement statements, as presented in Table 1.

Table 1. Requirement statements

ID	Requirement Statements
RQ1	Ability to obtain information on shop floor status, which consists of parts/orders being worked on, progress status of part operations, operating time of each part on each machine, and productive / non-productive time of production machines.
RQ2	Shop floor connectivity capabilities with PPIC in real-time.

Based on Table 1, the need for a CPPS is related to shop floor status information and the real-time connection between the shop floor and PPIC. Manually connected shop floor status has deficiencies in the data accuracy, leading to unreliable production activity control. Thus, RQ1 is a requirement for data acquisition to control production activities. The shop floor connection with PPIC in real-time is a requirement statement due to the problem of data feedback on production activity progress and PPIC. Thus, RQ2 is expressed as a requirement for data and information integration between the shop floor and PPIC.

The requirement statements are further elaborated into functional and non-functional requirements based on the requirement statements. Functional requirements are requirements or features that must exist in the system to meet user requirements. The functional requirement is categorized into 1) User interface requirement, 2) Processing requirement, 3) Storage requirement and 4) Control requirement, as described in Table 2. The functional requirements are mainly driven by the need for production activity control in the as-is system configuration.

Table 2. Functional requirements

Functional Requirement	Requirements
User Interface Requirement	The system can display production activity data (operator, part/order, machine, and production activity status).
	The system can display the time of production activities (productive time and non-productive time).
Processing Requirement	Production assignments in product routing and machine sequencing are retrieved from the ERP system.
	Production activity time data are acquired directly from CPPS without any operator intervention.
	The production assignment is assigned to an operator by a dispatcher and automatically stored in the RFID card.
Storage Requirement	Part/order progress-related data are to be stored.
	Machine activity-related data are to be stored.
Control Requirement	Data can be accessed via the internet through authorization.

3.3 CPPS Design Requirements

CPPS design requirements are determined by mapping the gap between as-is and to-be systems to meet the needs of the production activity control function, as presented in Table 3. There are two main CPPS objects: the customer order and the machine. RFID is used to identify part activities, including the operator handling the process and the machine being utilized. The operation of the machine spindle defines the machine's productivity state. The change of current detects the machine's status. Thus, a current sensor is applied to the CPPS. A microcontroller connected to a communication protocol is required to support real-time monitoring and ensure the connection between the shop floor and PPIC. The data acquisition is then stored in a cloud service. The data on the cloud service is then integrated into the ERP system for PPIC processing.

Table 3. Gap matrix mapping of as-is system vs. to-be system

Object	As-Is System	To-Be system	Requirements
Customer order	Part		
Machine	Machine spindle		
Sensor		Current sensor	Current sensor required
Machine	CNC machine and conventional machine		
Controller	-	Microcontroller	Microcontroller required
Production System	MTO industry		
PPIC system	ERP system		
Communication Protocol	-	Wifi, HTTP	
Data Acquisition Technology	-	Hardware: sensors, microcontrollers, RFID;	CPPS with sensors, microcontrollers, RFID
Data Storage Technology	Local host	Cloud database	Cloud connectivity
Raw Data	Logbook entry	Data from RFID and current sensors	Data acquired from RFID and current sensors
Resource Capability	Receives data from logbooks through ERP	Perform real-time data acquisition and data storage	Data processing of part progress and machine utilization

4. CPPS System Architecture

Figure 2 highlights the CPPS system architecture. The process begins with the ERP system setting the production plan based on each detailed part schedule. Each part is dispatched with a specific operator card to monitor the production activities. As the production activities progress, the current sensor and RFID will sense the various activities conducted by each operator at specific machines. The microcontroller functions as a receiver and processor of these activity data. Part activity-related data is identified through the RFID, and the current sensor captures machine activity-related data. These data are transferred by IoT microcontroller (NodeMCU ESP8266) to the cloud services by a Rest Application Programming Interface (API). A Rest API is a way for two devices to communicate using the HTTP technologies found in web browsers and cloud servers. The captured data in the cloud is then transferred to the ERP system for evaluation.

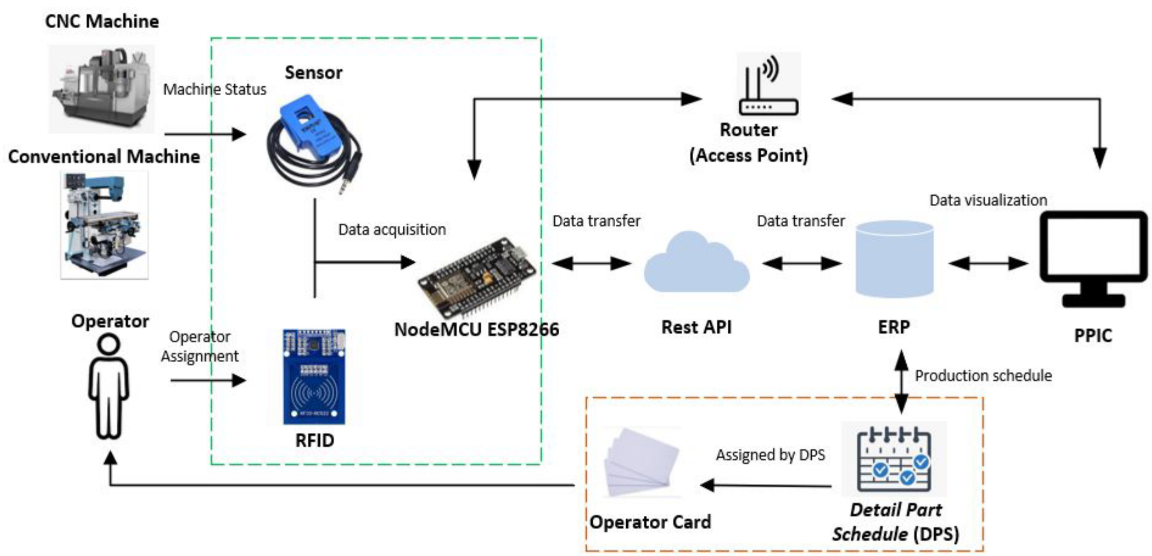

Figure 2. CPPS system architecture

4.1 CPPS Development

The CPPS development is conducted by improving the prototype designed by Adisasmita et al. (2022). The main changes to the previous prototype design is a printed circuit board and providing a CPPS casing to ensure stable operation in a shop floor environment. A jack is also added to provide modularity if a different type of sensor is used in the future. The hardware used in this CPPS included NodeMCU ESP8266 (microcontroller), current sensor SCT-013 (sensor), RFID reader/writer MIFARE RC522, LCD I2C, resistors, and capacitors, as shown in Figure 3. The CPPS unit utilizes an external DC power supply. Meanwhile, the software is developed using C++ for microcontrollers and PHP for cloud data processing.

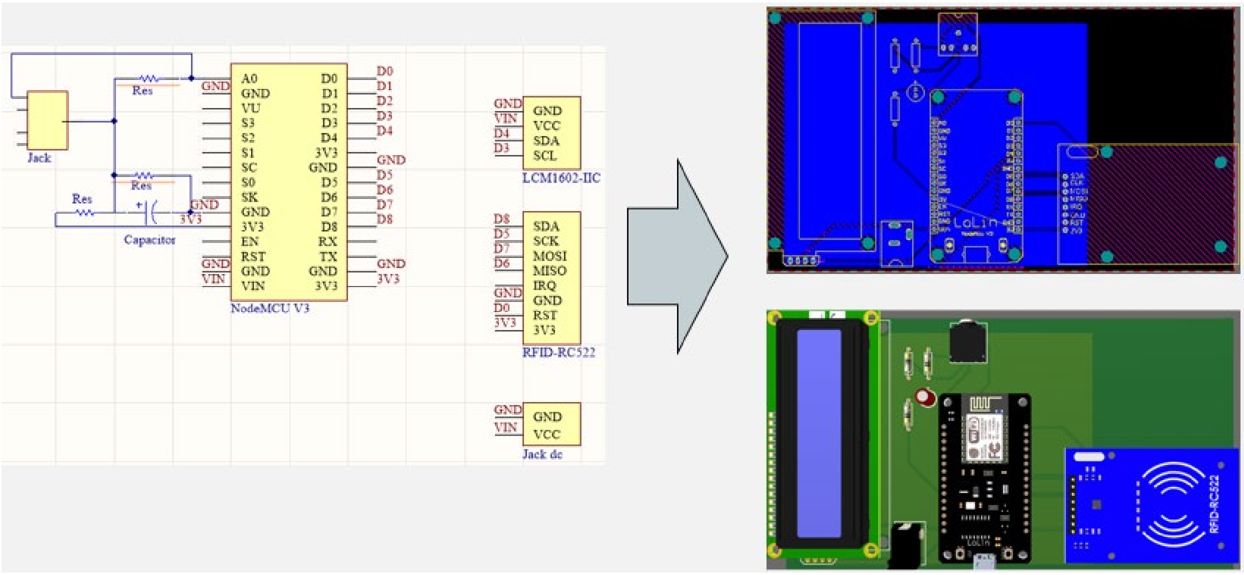

Figure 3. CPPS hardware design

5. Implementation and Discussion

5.1 CPPS Testing

The developed CPPS is tested to check the ability to detect machine activity. As shown in Figure 4a, the current acquisition from the CPPS is relatively stable to the current measuring instrument of Figure 4b. Figure 4c displays the actual current and power changes due to the activity of the machine spindle. Thus, the current sensor can detect whether the spindle is in operation, setup mode, or idle. The machine will consume more power when the spindle is active, or in other words, a higher current will be transferred from the electricity source to the machine. This status will be in reverse, where there will be less current flow when the machine is idle.

(a) (b) (c)

Figure 4. CPPS testing

5.2 CPPS Costing

The development of the CPPS was conducted in-house by purchasing the necessary bill of material. Table 4 present the cost structure of the developed CPPS, which consist of the cost of the main and supporting components. The main component consists of 12 materials, and the supporting component consist of 4 components. The price of the proposed CPPS per unit is IDR 235,240, or equivalent to USD 15.3. The developed CPPS cost is considered effective to an MTConnect standard controller having an average cost of USD 1,000.

Table 4. Cost structure

Main Component	Price (IDR)
NodeMCU ESP8266 V3	35,000
RFID RC522 Reader	16,000
Current Sensor (SCT-013)	55,000
Adaptor (DC 5V 2A)	15,000
DC Female Socket	550
Resistor (22 Ω)	100
Resistor (10 kΩ; 2pcs)	200
Capacitor (10 µF)	500
Audio Socket (3.5mm)	1,250
LCD Crystal (16x2 I2C)	24,000
Comb Socket (17 feet; 3pcs)	3,000
PCB print	60,000
Total cost of main components	210,600

Supporting Component	Price (IDR)
Electronic Box (X6)	15,000
Cooling Fan (DC 5V)	5,000
Buzzer (SFM-27)	4,550
Tapping Screw (#6x1,25)	90
Total cost of supporting components	24,640

CPPS Cost Structure	Price (IDR)
Cost of main components	210,600
Cost of supporting components	24,640
Total cost of CPPS	235,240

5.3 Validation

The CPPS development is validated by implementing the unit at two MTO industries. Three validation aspects have been conducted. First, data acquisition of part/order activities. Second, data acquisition to detect machine activities. Third, integration of data acquisition with the ERP system. The combination of RFID and current sensors identifies operator, part, and machine activity, as shown in Figure 5. The level of current will identify the status of the on/off. In combination with the first RFID scan, the part/order will be identified as the starting time at the machine. The variation level of the machine current will differentiate the machine status being non-productive, setup, or cutting time. The second RFID tapping will be marked as the finish time of the specified order/part at the specified machine.

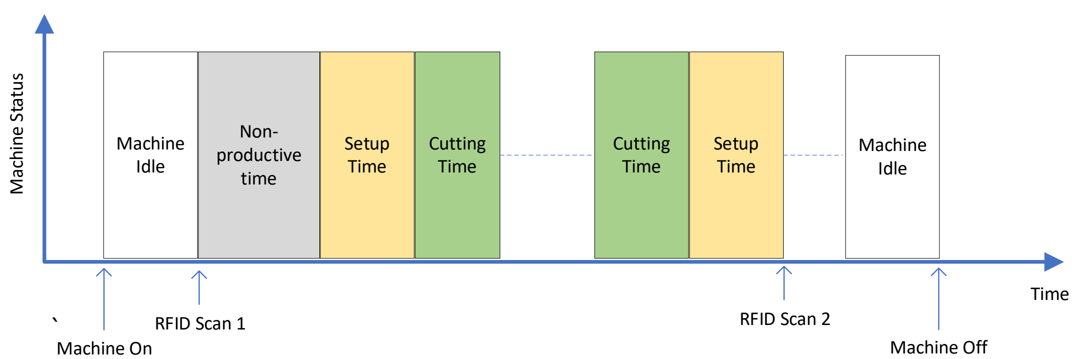

Figure 5. Part/Order and machine state changes

Table 5 is an example of the data collected by the CPPS in the form of date, operator, order ID, part ID, machine, and time calculation. The data provided fulfills the functional requirements as discussed in Section 3.3. The data acquisition is further transferred to the ERP system for evaluation and support basis for decision support for the PPIC Department.

Table 5. Data acquisition example

No.	Assignment Date	Operator Name	Order ID	Part ID	Position	Productive Time: Setup Time	Productive Time: Cutting Time	Productive Time: Productive Time	Non-Productive Time	Cycle Time
31	-	-	-	-	-	00:00:17	0	00:00:17	00:00:02	00:00:19
32	2022-08-22	Deni Ariki	ROTOR LUBE PUMP MC. JONAN	COVER HOUSING PUMP (Modifikasi)	Standard SM-5	00:00:08	0	00:00:08	00:00:02	00:00:10
33	2022-08-23	Faris Adha Wijaya	01-02 Stripper Plate	TUAS PEMUTAR	Hartford MATRIX 560AH	02:30:45	00:11:49	02:42:35	00:00:11	02:42:46
34	2022-08-23	Aditya Juang	ROLLER LONG SEAL MC EUROSICMA77	ROLLER LONG SEAL MC EUROSICMA77 LH	Hartford PRO-1000 SP	00:12:09	00:57:24	01:09:33	01:26:27	02:36:00

Cardin (2019) stated that a CPPS must have at least three essential capabilities: communication, computing, and control. Figure 5 and Table 5 show that the developed CPPS fulfills three main aspects of a CPPS: communication (both between the machine's physical system and the decision-making system), computing ability to calculate the productive time of operators and machines, and control in providing feedback. As stated by Lee (2020), data and information captured through CPPS can be further used for synthesizing production activity control of an MTO industry.

5.4 Initial Implementation of the Proposed CPPS

The proposed CPPS has been implemented in the MTO industry. The comparison between the manual logbook and CPPS is presented in Figure 6 for the cutting time and Figure 7 for the setup time. The horizontal line depicts the date of data acquisition, and the vertical line depicts the time consumed at the particular machine. Most of the time, the logbook for cutting time is higher than the CPPS recording. The rationale is that the operator does not enter the end of activity directly into the logbook due to some technical reason, thus leading to the inaccuracy of data.

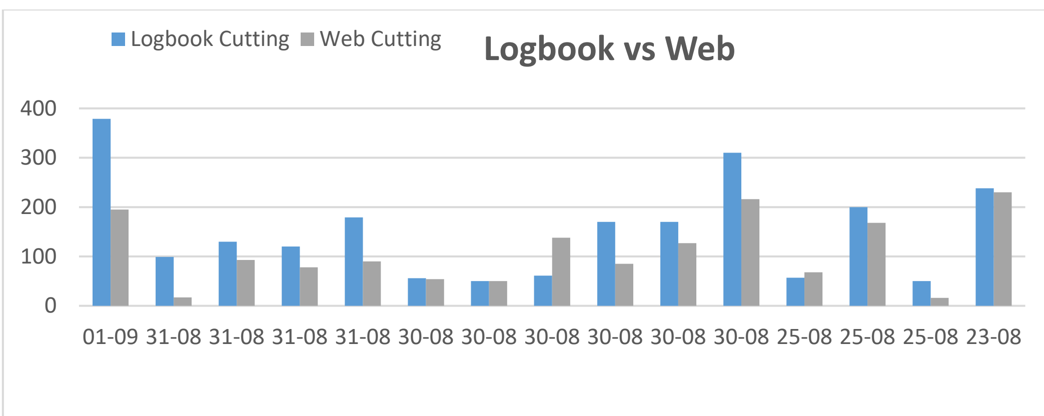

Figure 6. Logbook vs. CPPS recording for cutting time

On the other hand, the logbook for setup time reveals that it is difficult for the operator to identify nor input the setup time into the logbook, while CPPS consistently identifies the amount of setup time. Nevertheless, CPPS data acquisition is better because it is accurate and real-time. Thus, the developed CPPS has met three data quality and integrity requirements: complete, consistent, and correct (Schuh et al., 2017).

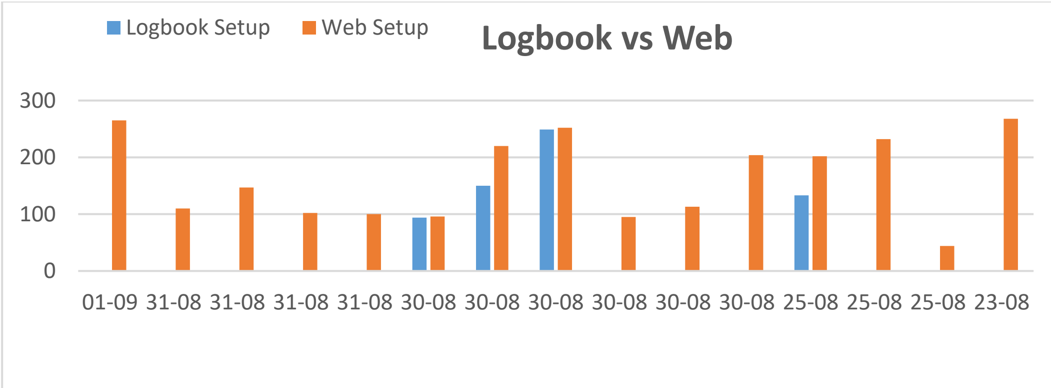

Figure 7. Logbook vs. CPPS recording for setup time

Aside from the data acquisition, it has been identified by MTO practitioners that the productivity data of the operator and machine gives precise feedback to the MTO management in evaluating the cost structure of each customer order. Cost evaluation before CPPS implementation is conducted in an aggregate manner where operator and machine costs are distributed roughly among orders being processed at a particular planning horizon.

6. Conclusion

This study has developed a cost-effective CPPS implemented for the MTO industry. The data acquired by the CPPS include part/order and machine activities on a real-time basis. The CPPS development was carried out through three steps: reviewing the as-is system, defining the to-be system, and identifying the gap analysis of the CPPS requirements. Initial implementation in the MTO industry proves that the proposed CPPS could monitor the production progress of customer orders and machining utilization, including setup and cutting time. The data acquisition also provides other potential decision support, such as direct cost evaluation (operator and machine) of each customer order. Future research and development will focus on utilizing learning algorithms to ensure that the response process of data collected by the CPPS can be executed intelligently and autonomously.

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Biographies

Anas Ma’ruf is currently an associate professor and a research member at the Manufacturing System Research Group, Bandung Institute of Technology. He graduated from the doctorate program in Mechanical and Structural Engineering at Toyohashi University of Technology, Japan. His research interests include production automation, intelligent manufacturing systems, and production planning and control. He is a board member of the Asia Pacific Industrial Engineering and Management Society and a member of IIE.

Rifqi Qinthara graduated with a bachelor’s degree in Industrial Engineering from Bandung Institute of Technology, Indonesia, in 2022. He is a research assistant at the Manufacturing System Research Group, Bandung Institute of Technology. Qinthara has completed several research projects related to Industry 4.0 and green energy. His current interest is the development of IoT devices.

Muhammad Rafif Rajendra Wiradikara graduated with a bachelor’s degree in Industrial Engineering from Bandung Institute of Technology, Indonesia, in 2022. Wiradikara has completed several research projects related to Industry 4.0 and green energy. He is a research assistant at the Manufacturing System Research Group, Bandung Institute of Technology. His current interest is in cloud computing and computer programming.