Cloud-based statistical process control mobile application development for smart manufacturing

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Abstract

Product quality is critical to manufacturing sectors because defective parts and production scraps affect business profitability and sustainability. In alignment with the Lean Six Sigma manufacturing approach, reducing process variability using statistical process control (SPC) is the primary strategy for controlling product quality. Motivated by the increased prevalence of mobile devices and their influences on the smart manufacturing environment in the industry 4.0 era, this study presents the development of the ProcMon app, a mobile-cloud application designed for factory SPC monitoring. The system consists of mobile devices, internet connectivity, and cloud services. The ProcMon app adopts a three-layer client-server architecture comprising the presentation, business, and data layers. The factory SPC monitoring is realized via automated control chart plotting, process capability Indices, and Nelson rules. A short message service alert is sent if out-of-control processes are detected. The ProcMon app is developed using two open-source software platforms: MIT App Inventor 2 and Google Workspace. This research demonstrated that MIT App Inventor 2 and Google Workspace offer a low-cost and less complex development approach for mobile cloud applications in manufacturing, benefiting nonprofessional programmers and stakeholders with a minimal budget. After completing app development, a system test was conducted using simulated data from a machining part fabrication case study for the app functional validation, and the acceptance test conducted by a focus group concluded that the ProcMon app meets the requirements for a low-cost, flexible, available 24/7, efficient, and easy-to-use application for SPC.

Keywords
Cloud services, smart manufacturing, statistical process control (SPC), mobile applications development, MIT App Inventor 2.

1. Introduction
Product quality is critical in the manufacturing sector, and thus, to increase business profitability and sustainability, quality tools and methodologies are necessary to reduce defective parts and production scraps (Sousa et al. 2017). Among the quality tools, statistical process control (SPC) is a popular industry standard methodology that aims to reduce process variability, which is the cause of most quality issues (Hrvačić 2018). In turn, such reduction improves process stability and capability (Montgomery 2013). One of the most widely used SPC tools for process quality control is the Shewhart control chart, which was introduced by Walter A. Shewhart in 1924 (Allkhafaji and Obeidy 2018). The Shewhart control chart monitors and controls a process to ensure that it will behave predictably to produce conforming products constantly, while tracking variations in the process that may affect the quality of products (Madanhire and Mbohwa 2016). By itself, however, the Shewhart control chart does not provide information regarding the associated judgment on process stability. Instead, various supplementary run rules have been proposed for analyzing data patterns within the control limits of control charts (Zaman and Hassan 2021). The Nelson's run rules proposed by Lloyd S. Nelson are the most popular in this area (Montgomery 2013). According to Aslam et al. (2019), as the SPC approach is commonly applied to monitor and improve manufacturing process capabilities by reducing process variations, process capability indices (PCIs) are established to monitor the variability of a process. In general, the PCIs C_p and C_{pk} are commonly used to provide a quantitative ratio for comparing the specifications of a product to the process's performance capability (Pyzdek and Keller 2010; Montgomery 2013).

The convergence of mobile and cloud computing has led to a new era of mobile-cloud services in education, healthcare, business, and social networks (Kim 2018). As reported by Marko (2022): 1. more than 5 billion people worldwide own mobile devices as of 2019, 2. 71 billion people in the world own a smartphone in 2019, 3. 194 billion mobile phone apps were downloaded in 2019, 4. two-thirds of the world is now connected via mobile devices, and 5. mobile device owners worldwide will increase to 7.33 billion by 2023. These observations show that the mobile device has become a necessity in our daily lives instead of a luxury item. Hence, this research is motivated by the increased prevalence of mobile devices and their influences on the smart manufacturing environment in the industry 4.0 era. The adoption of Industry 4.0 in recent years has resulted in the digitization of manufacturing infrastructure into cyber-physical systems (Doyle and Cosgrove 2019). As Samir et al. (2019) highlight, mobile devices play a crucial role in integrating manufacturing systems with information technologies (ITs), providing decision-makers with updated information when needed. For example, Wu et al. (2020) presented a real-time logistics system tracking and management mobile app developed for an automotive part company. Bu et al. (2021) used mobile devices as a human–machine interface to track production situations in real time, optimize production scheduling, perform remote maintenance, and obtain user feedback. Despite the increased emphasis of the manufacturing sector on moving toward Industry 4.0, the literature review shows that the use of mobile apps to monitor manufacturing process stability is still in its infancy. Process monitoring is still run primarily with software set up on the server or personal computer stationed in the factory.

This research presents a pioneering effort to develop a mobile-cloud-centric SPC system that runs on cloud services and mobile devices. The proposed ProcMon app is an online SPC tool for monitoring manufacturing process stability using the Shewhart control chart, PCI, and Nelson rules. The system setup has low implementation and maintenance costs, in contrast with existing available solutions commonly customized for factory manufacturing execution system (MES) facilities with substantial investments in software and basic IT infrastructure. The proposed mobile-cloud app was developed using MIT App Inventor 2 and the Google Workspace open-source platforms. The developed mobile app offers the following advantages to smart manufacturing: 1. Dynamic information connection to the production shop floor for remote process monitoring and decision making, 2. Portability and mobility provided by mobile devices, 3. Round-the-clock data availability by advancing broadband network availability and high-speed mobile broadband coverage in the 4G/5G era, 4. Flexibility to be customized in accordance with factory needs, 5. Interactivity with easy-to-use graphical user interface (GUI), and 6. Secured data access with credential log-ins.

The remainder of this paper is organized as follows. The second section presents literature review on SPC monitoring with control chart and Nelson rules, overview of MIT App Inventor 2 and the Google Workspace platforms. The third section describes the system architecture and software development of the ProcMon app. The fourth section explains the operations of the ProcMon app. The fifth section provides validations of the ProcMon app, and lastly, the conclusion drawn from the study.

2. Literature review

2.1 SPC monitoring with control chart and Nelson rules

As summarized by Montgomery (2013), quality is a critical part in manufacturing industry as quality means the products' fitness of use, it is inversely proportional to variability, and quality improvement is the effort to reduce variability in processes and products. Also highlighted by Hrvačić (2018), process variability is the cause of the most quality issues, and one of the typical quality tools for quality improvement is Statistical Process Control (SPC). SPC is a collection of problem-solving tools to achieve process stability and improve capability by reducing variabilities. SPC consist of seven major tools: Histogram or stem-and-leaf plot, check sheet, pareto chart, cause-and-effect diagram, defect concentration diagram, scatter diagram, and control chart. Among the seven, control chart introduced by Walter A. Shewhart in 1924 is the most prominently applied in the manufacturing industry for process monitoring. The control chart facilitates process control by detecting and analyzing the impact of variability from both random causes and special causes on the process (Pyzdek and Keller 2010; Montgomery 2013). For example, an X-bar and R (range) chart control charts are used in tandem to monitor the mean and range of a process quality characteristic over time. In general, the control chart is a graphical display of a quality characteristic that has been measured or computed from a sample versus the sample number or time, and it is recommended to use at least 20 to 25 samples to establish a control chart. The chart contains a centerline representing the average value of the quality characteristic corresponding to the in-control state. Two other horizontal lines called the upper control limit (UCL) and the lower control limit (LCL) are required in the control chart. (Figure 1)

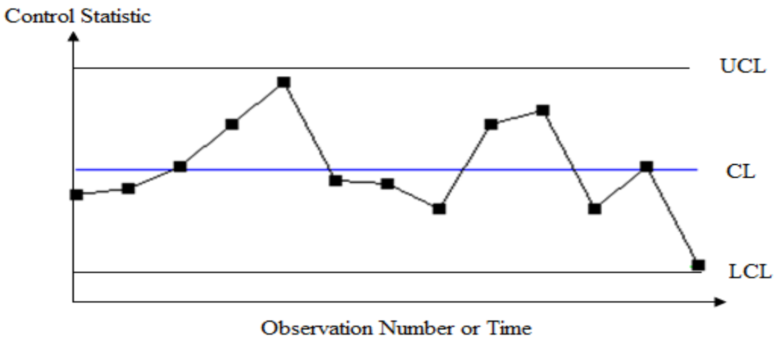


Figure 1. Control chart

The control limits are usually set at ±3 standard deviations from central line. The center line (CL), upper control limit (UCL) and lower control limit (LCL) for the $\bar{x}$ chart are computed by:

$$CL_{\bar{x}} = \bar{\bar{x}}$$
$$UCL_{\bar{x}} = \bar{\bar{x}} + 3\sigma_{\bar{x}}$$
$$LCL_{\bar{x}} = \bar{\bar{x}} - 3\sigma_{\bar{x}}$$

and R charts are computed by:

$$CL_R = \bar{R}$$
$$UCL_R = \bar{R} + 3\sigma_R$$
$$LCL_R = \bar{R} - 3\sigma_R$$

where $\sigma_{\bar{x}}$ is population standard deviation of the subgroup averages and σ_R is population standard deviation of the range.

Generally, a process is considered statistically stable if the observation point lies between the UCL and LCL of the control chart. If the plotted points behave randomly up and down within the control limits, only natural variation is present. Otherwise, the process stability is disturbed by the presence of unnatural variation due to special assignable causes. However, by itself, the control chart does not provide information on the associated judgment on process stability and the presence of unnatural variations. To overcome this limitation, the Nelson rules can be applied to analyze the data patterns within the control limits of control charts (Montgomery 2013; Zaman and Hassan 2021). The Nelson rules are summarized in Table 1.

Table 1. Nelson rules (Nelson 1984)

Rule	Description
1	One point is more than 3 standard deviations (σ) from the mean
2	Nine points in a row are on the same side of the mean
3	Six points in a row are continuously increasing (or decreasing)
4	Fourteen points in a row alternate in direction, increasing then decreasing.
5	Two out of three points in a row are more than 2σ from the mean in the same direction.
6	Four out of five points in a row are more than 1σ from the mean in the same direction
7	Fifteen points in a row are within 1σ of the mean on either side of the mean.
8	Eight points in a row exist with none within 1σ of the mean and the points are in both directions from the mean.

2.2 Open-Source App development platforms: MIT App Inventor 2 and Google Workspace

MIT App Inventor and Google Workspace are two open-source software platforms used in developing the ProcMon app. MIT App Inventor 2 is a web-based visual programming integrated development environment (IDE) for creating mobile apps. The programming environment has been designed applying a block programming approach, such that a program is created by connecting blocks of program components like a jigsaw puzzle. Each app is specified by a project that consists of a set of user interface components, while the behaviour of the components is specified using a block-based graphical programming language (Patton et al. 2019). This programming approach lowers the barrier of mobile app programming, benefiting people with minimal or no programming experience who wish to create mobile apps (Kang et al. 2015; Taufiq et al. 2019). In addition, this block programming approach exhibits the advantage of reducing programming errors, because it provides visual guidance for assembling and understanding program structure. Another key feature of App Inventor is live programming via the use of the App inventor companion app without the need of reinstalling the app every time changes are made to the program. Any changes made to the program will be realized in real-time in the running companion app on the mobile device (Schiller et al. 2014). To date, 14.9 million registered users from over 195 countries have used the App Inventor web page to build over 67.8 million apps (MIT App Inventor 2022).

Google Workspace (formerly known as Google Apps and later G Suite) is a collection of software and products developed for cloud computing, productivity, and collaboration tools running on the Google Cloud Platform, a cloud infrastructure offered by Google as a service to provide a serverless computing environment (Wikipedia - Google Workspace 2022). Among the tools, Google Drive allows users to upload any type of file to the cloud, share them with others, and access and sync files between computers or mobile devices. Google Docs is an online word processor, and Google Sheets is a spreadsheet program. Google Forms is a tool that facilitates the collection of information from users via a personalized survey or quiz form. Google Apps Script is a JavaScript cloud scripting platform for lightweight application development; it enables the automation of tasks across Google products and third-party services (Google Workspace-How teams of all sizes connect, create and collaborate 2022). All these cloud-based productivity and collaboration tools allow seamless synchronization among multiple devices when accessing information without significant investment in hardware infrastructure.

3. ProcMon app system

3.1 System design

The ProcMon app system's design applies mobile-cloud computing, which groups mobile devices, Internet connectivity, and cloud services, enabling real-time access to factory SPC information, anytime and anyplace (Figure 2).

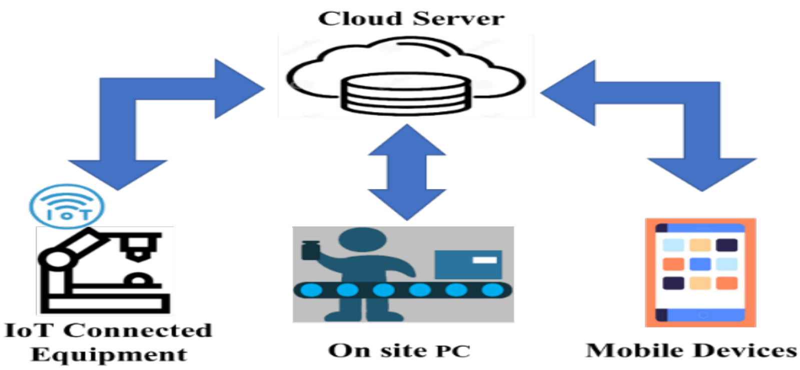


Figure 2. System design

The ProcMon app adopted a three-layer client-server architecture (Figure 3), which consists of the presentation, business, and data layers (Gruhn and Köhler 2006; Kim 2013).

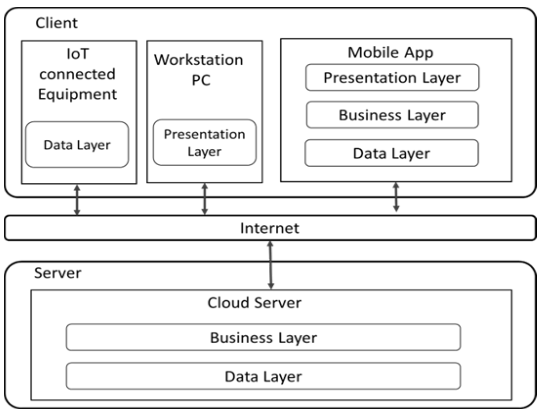


Figure 3. ProcMon app architecture

The presentation layer consists of GUI modules, interfacing the user and the business layer by displaying information to and soliciting feedback from the user. The business layer handles system operations, including data transfer, update, and processing; performing analysis when new data are updated; moving data across layers; data refreshing of the GUI; Nelson rules checking; user authentication; short message service (SMS); and control chart generations. The data layer in the cloud server is the data warehouse wherein client devices apply to the devices' local data storage. The manufacturing SPC data are stored in Google Drive in the cloud server.

As presented in Figure 4, three possible data sources are available for the ProcMon App SPC database: 1. Measurement data are updated automatically in the form of .csv files from any Internet of things (IoT)-connected equipment. 2. Measurement data are manually keyed into Google Form using a PC. 3. Measurement data are manually keyed into Google Form using the ProcMon App. Subsequently, the computation of statistical values, Shewhart control chart generation, and run rule checking using Nelson rules are performed in the cloud server. Lastly, all the computed data, control charts, and Nelson rules checking results, which are refreshed frequently, were made accessible to client devices via various GUIs of the mobile app.

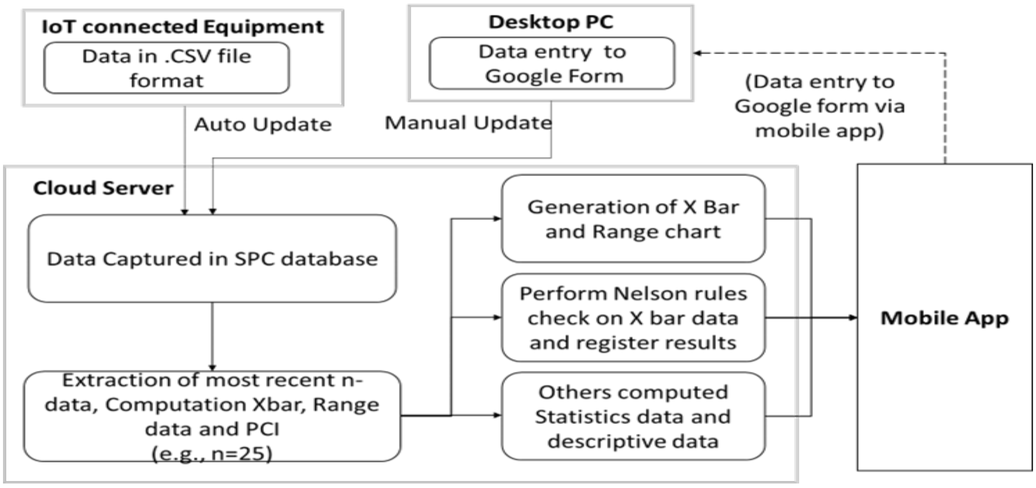
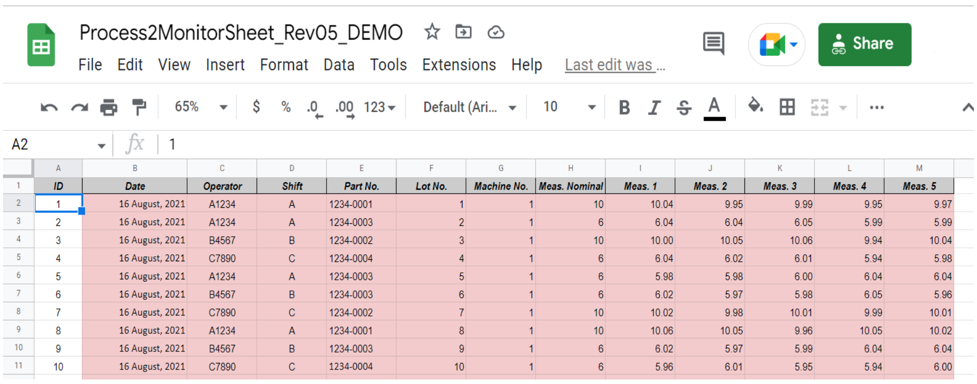


Figure 4. System data flow

3.2 ProcMon app software development

At the cloud server end, Google Workspace tools, i.e., Google Drive, Google Sheets, Google Forms, and Google App Scripts, are utilized. First, as illustrated in Figures 8(c) and 8(d), data entry forms for the monitored process were implemented using Google Forms, providing a web-based form accessible to authorized users with the provided share link URL using a PC or mobile devices.

Second, in the server's data layer, SPC database, SPC data computation, and control chart generation were implemented in the form of a spreadsheet using Google Sheets (Figure 5) and stored in Google Drive under the Google Cloud Platform.



ID	Date	Operator	Shift	Part No.	Lot No.	Machine No.	Meas. Nominal	Meas. 1	Meas. 2	Meas. 3	Meas. 4	Meas. 5
1	16 August, 2021	A1234	A	1234-0001	1	1	10	10.04	9.95	9.99	9.95	9.97
2	16 August, 2021	A1234	A	1234-0003	2	1	6	6.04	6.04	6.05	5.99	5.99
3	16 August, 2021	B4567	B	1234-0002	3	1	10	10.00	10.05	10.06	9.94	10.04
4	16 August, 2021	C7890	C	1234-0004	4	1	6	6.04	6.02	6.01	5.94	5.98
5	16 August, 2021	A1234	A	1234-0003	5	1	6	5.98	5.98	6.00	6.04	6.04
6	16 August, 2021	B4567	B	1234-0003	6	1	6	6.02	5.97	5.98	6.05	5.96
7	16 August, 2021	C7890	C	1234-0002	7	1	10	10.02	9.98	10.01	9.99	10.01
8	16 August, 2021	A1234	A	1234-0001	8	1	10	10.06	10.05	9.96	10.05	10.02
9	16 August, 2021	B4567	B	1234-0003	9	1	6	6.02	5.97	5.99	6.04	6.04
10	16 August, 2021	C7890	C	1234-0004	10	1	6	5.96	6.01	5.95	5.94	6.00

Figure 5. SPC database implemented with Google sheet

Third, App Scripts were implemented using the Apps Script Interface within Google Sheets to automate tasks (Figure 6). For example, data extraction and movement across sheets, performing GET and PUT instructions when exchanging data with the Android app, and Nelson rules algorithms are automation scripts implemented by Google App Scripts.

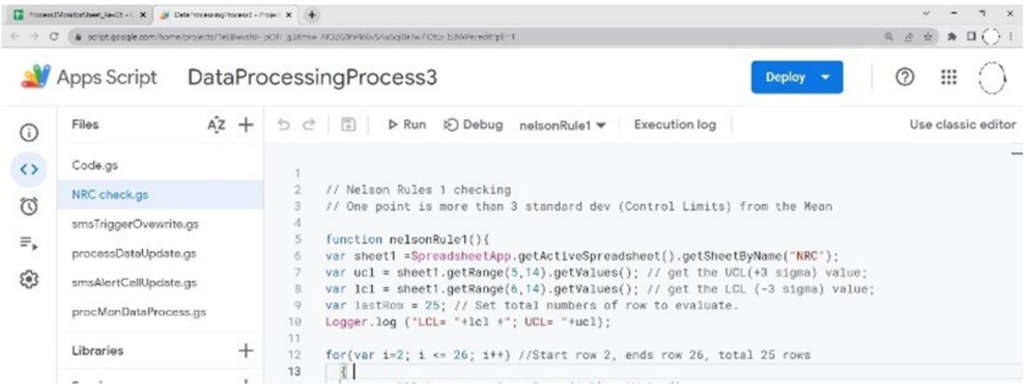
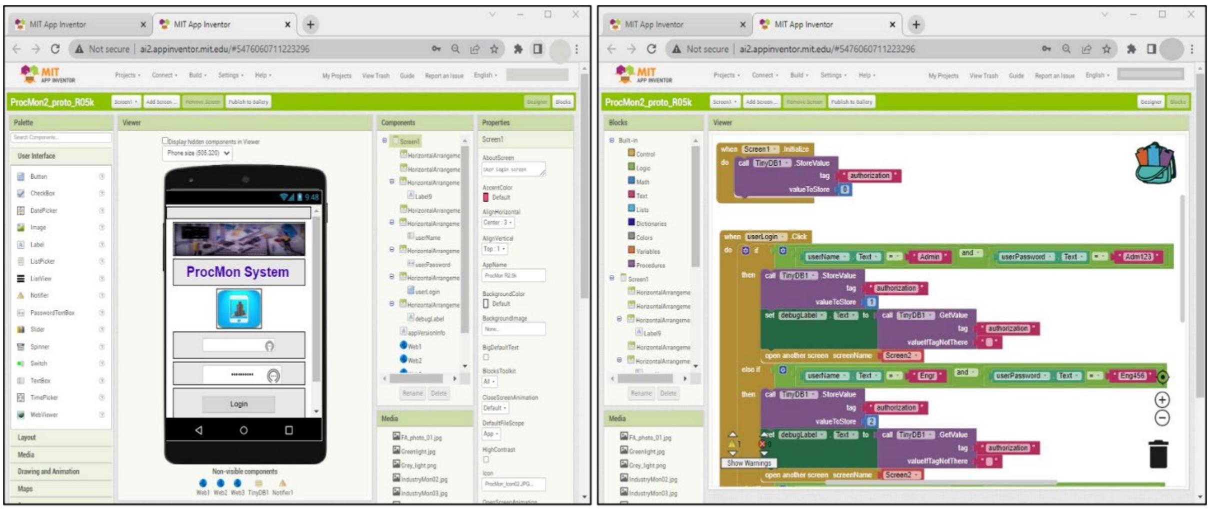


Figure 6. Google App Scripts development interface

Mobile devices play the role of thin clients in the ProcMon system, wherein the ProcMon app was developed using the App Inventor platform. When developing the ProcMon app, App Inventor's designer interface creates the appearance and layout of the app, while Blocks Editor constructs the back-end logic that determines how the app works. Figures 7(a) and 7(b) show the ProcMon app user log-in GUI creation in the Designer and Block Editor environments, respectively. Live testing with the App Inventor companion app was used for app debugging purposes.



(a) (b)

Figure 7. (a) App inventor designer interface (b) App inventor block editor

4. ProcMon app operations

In the ProcMon app, there are three types of user credentials defined: Admin, Engineer, and Operator. Admin or Engineer users will have similar access privileges to view manufacturing SPC information; however, making changes to the app setup parameters is restricted to Admin users only. The operator can only perform manual data entry via the app. At the user log-in GUI [Figure 8(a)], when log-in with operator credential, the user will enter the data entry form selection GUI [Figure 8(b)]. In this GUI, if the process is set up to update data automatically via IoT connection, then the selection button will appear as grey and deactivated, preventing access by the user. Here, the user may click the button to perform manual data updating for the process of interest. Thereafter, the app will transition to the data entry form, displaying the Google form in the GUI web viewer window [Figure 8(c)]. Once data entry is completed, clicking the [Submit] button at the end of the page [Figure 8(d)] will save the new data to the manufacturing SPC database, and the GUI will revert to the top of a fresh data entry form. In the ProcMon app, clicking the screen title on all GUIs will allow the user to leave the GUI and revert to prior GUIs.

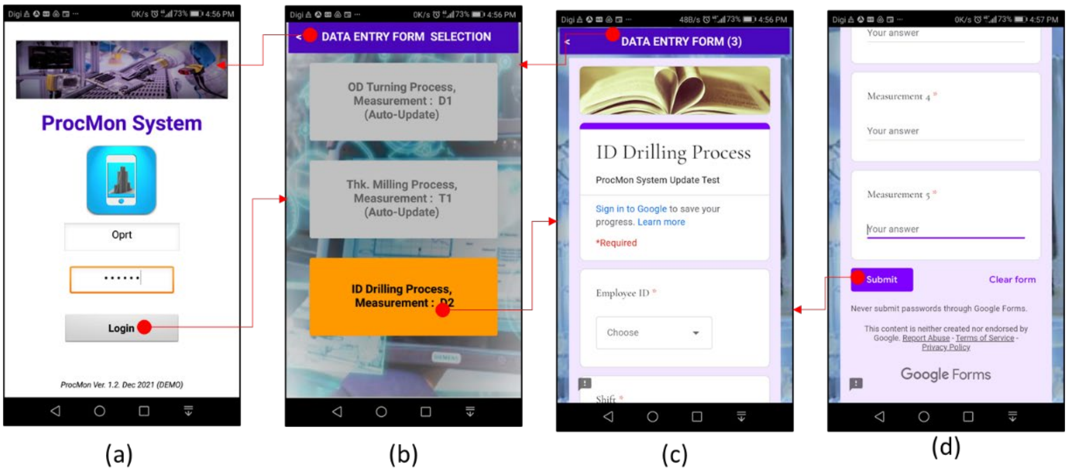


Figure 8. GUIs for manual data updating

When log-in with Admin or Engineer credentials, the wire flow is illustrated in Figure 9. Users will be greeted by the Dashboard GUI, with three large selection buttons representing each process under monitoring. The buttons' label displays the process name, measurement name, and PCIs [Figure 9(b)]. The button also functions as a visual alert indicator for the overall process status, with colour codes to indicate the state of process stability: 1. Red (process out of control), 2. Yellow (process in control, Nelson rules violation detected), and 3. Green (process in control with good C_{pk} value).

Selecting either one of the process buttons will transfer to the control chart GUI for the process of interest [Figure 9(c)]. In the control chart GUI, the X-bar and the range chart are arranged in parallel and displayed in one screen for users to fully view process variability over time. Selecting the [Summary Statistics] button will transition to the Summary Statistics GUI for the user to scrutinize the process monitoring information further.

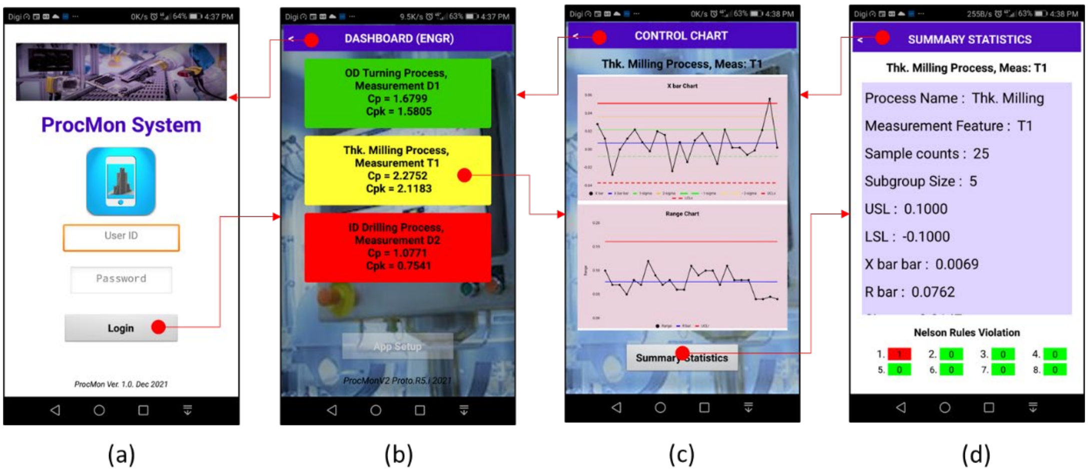
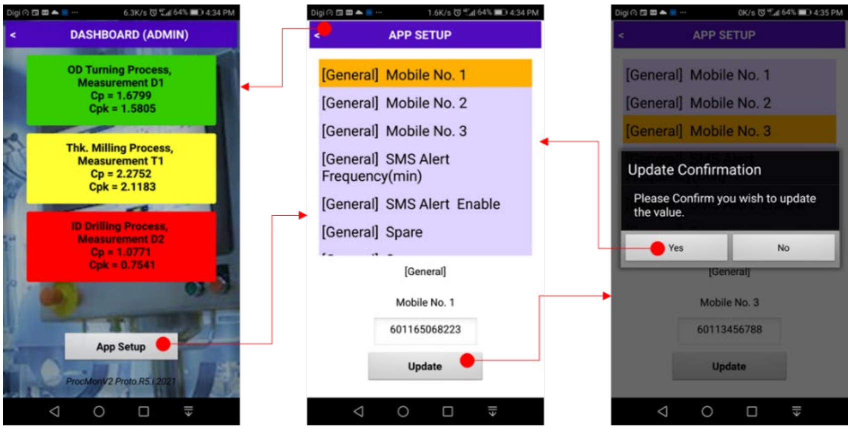


Figure 9. GUIs for SPC monitoring

In the Summary Statistics GUI, key process information and a graphical display of the breakdown of Nelson rules violations are presented [Figure 9(d)]. In this GUI, a scroll-down list design was applied to fit all the available statistical parameters within a limited screen area while not compromising legibility by cramping all the information with small fonts. At the lower corner of the GUI, the Nelson rules results are displayed compactly with a graphical array that combines rule number and the number of violations for each rule within a box with a colour-coded background. The colour coding used is red for violation detected and green for no violation detected. This arrangement gives the user a clear and concise indication of the Nelson rules results.

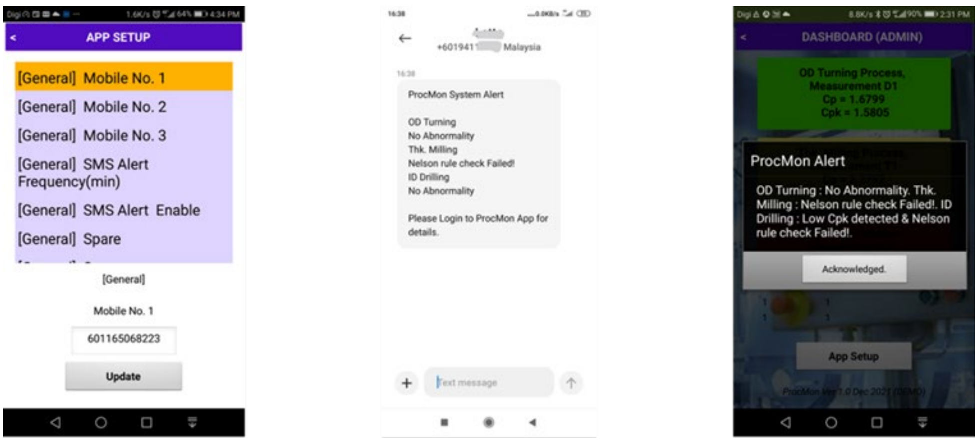
The ProcMon app could be customized to suit different process monitoring requirements using the App Setup GUI [Figure 10(b)]. However, access to this GUI is exclusive to Admin users. When log-in as Admin, the user may select the [App Setup] button to enter the App setup GUI. When log-in as Engineer, the [App Setup] button will be greyed out and deactivated, restricting access [Figure 10(b)]. In this GUI, the user can scroll through a list of accessible setup parameters and select the parameter of interest by clicking on the item on the scroll-down list. Subsequently, the currently saved value of that parameter will be retrieved from the cloud server and displayed in the text box at the bottom of the screen. The user can modify the parameter settings in the same text box and press the [Update] button and then the [Yes] button in the Update confirmation pop-up window [Figure 10(c)] to update the App setup database in the cloud server.



(a) (b) (c)

Figure 10. GUIs for App setup

To enhance the effectiveness of SPC, the ProcMon app was designed with an SMS alert feature when process instability is detected. When low C_{pk} or Nelson rules violations are detected, SMS alerts will be triggered and sent to the pre-registered users. By using the App setup GUI, the SMS alert feature can be set up by customizing as follows: 1. enable/disable alerts of low C_{pk}, Nelson rules alert individually, or combined; 2. alert sending frequency; and 3. registration of target mobile phone number into the app setup database [Figure 11(a)]. SMS messages [Figure 11(b)] will be sent out repeatedly in the predefined time interval and can only be deactivated when the admin user acknowledges the alert [Figure 11(c)].



(a) (b) (c)

Figure 11: GUIs for user alert messaging

5. ProcMon app validations

After completing the ProcMon app system integration and the iterative debugging, a system test was conducted to validate system functionality under various usage conditions in the real world and provide the app developer with a first-hand user experience. The system test cases were conducted using simulated data from a local machining shop's part fabrication case study. The test cases are presented in Table 2. The ProcMon app passed all the test cases conducted by the developer at the end of app development.

Table 2. Test cases for system testing

ID	Test case Description	Actor
TC.S01	Operator Log-in and Data entry Test.	Operator
TC.S02	Engineer Log-in, Dashboard View, Control Chart View and Statistics Summary View	Engineer
TC.S03	Admin Login, Dashboard View, Control Chart View and Statistics Summary View	Admin
TC.S04	User alert Messaging Test	Admin
TC.S05	App Setup data Updating	Admin

To validate if the ProcMon app meets the requirements for an SPC monitoring app from the aspects of functionality and user experience, an acceptance test was conducted with the help of a focus group consisting of 10 participants from the manufacturing industry. The focus group comprised of three process engineers, two quality assurance engineers, two product engineers, and three test engineers from a local electronics manufacturing services company. They were provided with an overview of the app's features, followed by installing and testing the app on their mobile phones. Subsequently, the participants were invited to answer a questionnaire survey, and the survey results are summarized in Table 3.

Table 3. Summary of acceptance test questionnaires results

ID	Survey Questions	Agree	Neutral	Disagree
(a)	Systems Design Requirements			
a.1	This app is a low-cost solution for real-time SPC monitoring.	100.0%	0.0%	0.0%
a. 2	The app is flexible and easy to customize.	100.0%	0.0%	0.0%
a.3	This app provides 24/7 and "on-the-go" access to SPC information.	100.0%	0.0%	0.0%
a.4	Password-protected log-in provides adequate data security.	90.0%	10.0%	0.0%
a.5	For SPC monitoring, SMS messaging is an effective user alert feature.	60.0%	30.0%	10.0%
a.6	The app's GUI layout is neat and clear.	90.0%	10.0%	0.0%
a.7	This app automates and simplifies the computation, data analysis, and control chart generation for SPC monitoring.	100.0%	0.0%	0.0%
a.9	This app is an efficient tool for factory SPC monitoring.	90.0%	10.0%	0.0%
(b)	Mobile app user experience			
b.1	The app operation is responsive.	100.0%	0.0%	0.0%
b.2	The screen information is updated on a regular basis.	100.0%	0.0%	0.0%
b.3	The GUI flow is easy to navigate and well-designed.	90.0%	10.0%	0.0%
b.4	The GUI design theme is appropriate and comfortable to view.	90.0%	10.0%	0.0%
b.5	The GUI's content and text are easily readable.	100.0%	0.0%	0.0%
b.6	The language used in the GUI is concise and easy to understand.	100.0%	0.0%	0.0%

b.7	The GUI buttons and their layout are intuitive.	100.0%	0.0%	0.0%

From the focus group feedback, all the participants agreed that the app meets the requirements for a low-cost, flexible, available 24/7, efficient, and easy-to-use SPC monitoring app.

6. Conclusions

This research demonstrated the successful development of the ProcMon app, a mobile-cloud app for online SPC monitoring, by combining the use of MIT App Inventor 2 and Google Workspace platforms. The ProcMon app features easy-to-use process monitoring capabilities, such as a control chart, PCI, and Nelson rules. Real-time SMS alerts is sent if a process is out of control. The developed system is a mobile-cloud multilayer architecture app that can operate across heterogeneous computing platforms. It uses Android mobile devices, Google cloud service, and Internet connectivity to provide factory personnel with an on-the-go process monitoring service. The acceptance test concluded that the app meets the requirements of low cost, flexible, available 24/7, efficient, and easy-to-use SPC app. In addition, this research also demonstrated two advantages of combining MIT App Inventor 2 and the Google Workspace platform in developing mobile–cloud applications. First, this approach incurs minimum financial costs due to the free or minimal cost of the open-source and web-based development platforms, eliminating the need for hefty setup investments and maintenance costs of hardware setup and software licensing. Second, this approach lowers the technical barrier for developing a mobile–cloud app for nonprofessional programmers. App Inventor's "what you see is what you get" editor and block-based programming language approach significantly reduce the complexity of coding work for app development. Google Workspace provides readily available cloud-based storage access and open-source productivity and collaboration tools that are user-friendly and do not require complicated configuration and setup efforts during the application development. As a research contribution, this study effectively illustrates the construction of a mobile-cloud app for SPC monitoring by using these two open-source software platforms which will considerably help prototyping or proof-of-concept for mobile-cloud app or smart manufacturing projects in future works.

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