IDENTIFYING VARIABILITY KEY CHARACTERISTICS FOR AUTOMATION DESIGN - A CASE STUDY OF FINISHING PROCESS

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Abstract

This paper describes an investigation of human interaction with process variability (i.e. variability not introduced by the humans themselves) in a manual manufacturing process. The process studied is grinding-polishing of high-value metal components, to evaluate the extent of the variability and how the operators applied their skills to overcome it. The research methods include analysis of documentation, observation and video recording and interviews. The results indicate that humans are able to adapt to variability in the parts and tools in order to deliver the product within specification. This suggests unconscious and automated behaviour meaning that the procedures executed are embedded in the minds of the operators. Vision and tactile senses were mainly used to check work progress and control critical features (Key Characteristics). Based on the findings of this and other case study, a framework will be developed to categorise variability in manual manufacturing processes to support the design of an automated solution.

Keywords: Case study, Complexity, Uncertainty, Key characteristics, Variability

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1 INTRODUCTION

In manufacturing, automation has replaced several dangerous, mundane and routine manual operations, for example, transportation of heavy parts, stamping of large parts and spot welding. However, skilled operators still carry out critical manual processes in various industries such as aerospace, automotive and heavy-machinery. The design of a solution to automate these manual processes might be difficult because some elements such as the tasks may vary from process to process. These variations typically require the operators to adapt to the tasks continuously to achieve the desired outcomes of the process (Sandom & Harvey 2004).

In the manufacturing context, variability can be defined in many ways, in this paper, variability is defined as any inherent deviation from pre-specified requirements. In the literature, variability is suggested as a main cause of lack of robustness in production processes and should be controlled to achieve acceptable quality outcomes (Glodek et al. 2006) (MacDonald 2003). Manufacturing variability could be introduced by the inputs and resources used in the process. For example, manufactured parts will have variations from the nominal dimensional values or the tools might behave differently under various working conditions due to wear, inadequate maintenance or misuse. The human operators are typically able to take in various in-process cues and make the appropriate adjustment by referring to rules, knowledge or skills acquired through experience (Rasmussen 1983).

The automation of these processes is challenging due to the complexity and cost of the hardware and software required. In order to ensure the automation design is right-first-time, a method to identify and characterise the variability in manual processes through observing the human interactions is proposed. The identified process variabilities are linked to the Key Characteristics, which are the critical requirements that must be controlled during the process.

The proposed method is applied to a case study of a grinding and polishing process of high value metallic components. The objectives are to identify the tasks performed by the operators, and the variability managed by them. The output of this paper will be used for assessing the difficulty of automating the process in the next stage of the research. The study was carefully constructed to avoid variability introduced by the human due to fatigue, motivation etc.

2 LITERATURE REVIEW

A manufacturing process transforms inputs into outputs through a series of connected and goal oriented tasks using a number of resources, including equipment, facilities and personnel. Variability may come from many different sources, which have not been contemplated in the specifications defined for the inputs, outputs, resources or tasks. The National Institute of Standards and Technology (NIST) classifies variability into two categories: controlled variability and uncontrolled variability. Controlled variability is defined by a stable and consistent pattern of variation over time. An example of controlled variability in manufacturing is machine settings. Uncontrolled variability is distinguished by a pattern of variation that changes over time, therefore unpredictable (National Institute of Standards and Technology 2016). Examples of uncontrolled variability in manufacturing are power fluctuations and room humidity.

There are many well-established approaches to determine and control variability affecting a manufacturing process, e.g. Statistical Process Control (Loose et al. 2008; Apley & Shi 2001), Total Quality Management (Montgomery 2008) or Six-Sigma (Dai & Yang 2011). Other authors have created methods to evaluate the impact of process variability on product quality and performance. For example, Antony et al. (Antony et al. 1999) identified seven factors which have some impact on the critical characteristic, analysed through statistical analysis to find which factors have the highest impact, and used this information to reduce variability in this critical characteristic. Thornton (Thornton 1999) proposed a Key Characteristic (KCs) method to identify where product quality will be most significantly affected by variation. A feature in the product is a Key Characteristic if the variation from the specification has considerable impact on the fit, performance, or service life of the product. A Key Characteristic is any attribute of an output, input or task that is quantifiable and whose variations from the expected have an inadmissible impact on the cost, performance, or safety of the output (Thornton 2004). These methods can be used to identify variability in the processes but, it is often unclear how the variability is influenced or reduced by the operators' skills and strategies in manual tasks due to the tacit and implicit nature (Sandom & Harvey 2004).

In processes still executed by humans in industry, most of the time they are dealing with complex tasks (Greitzer 2005; Boot et al. 2010) which need cognitive and physical skills as well as dexterity in order to be performed. Variability has been identified as a contributor to complexity by many authors (Wood 1986; Campbell 1988; Xiao et al. 1996; Carey and Kacmar 1997; Williams 1999; Bell and Ruthven 2004; Liu and Li 2012). Therefore, it is interesting to understand complexity and its implications for manufacturing processes. Although there is no universally accepted definition of task complexity (Liu & Li 2012), some authors have tried to define complexity, separating subjective complexity (complexity seen from the executer of the task perspective) from objective complexity and complexity from difficulty. Objective task complexity has been defined as the perspective which takes into account only task characteristics, independently from the performers as opposed to a subjective task complexity perspective which considers task complexity as a combination of qualities of the task and task performer characteristics (Wood et al. 1987). This paper is more concerned about objective complexity as it is relevant to automation.

Campbell's (1988) complexity model states that complex tasks have a number of the following characteristics: multiple paths, multiple outcomes, opposed correlation among paths, and uncertain or probabilistic associations. Campbell defines a complex task as one where the task performer is requested to utilise high cognitive skills. Task complexity increases as goal discrepancy increases, i.e.: if achieving one requested output differs with achieving another desired output. On the contrary, if all paths (i.e. alternatives) are likely to reach the same desirable outcome, this redundancy may reduce task complexity. The more highly structured the problem of a task (i.e. the more defined are its information requirements, process, and outcomes), the clearer the performer knows the basic elements of a task, consequently, more accurately s/he is able to determine what kind of information s/he needs and what processes are required for its completion. Simple tasks are typically tasks with structured problems (Nembhard & Osothsilp 2002). Campbell's work mentions the factors of task complexity, however does not indicate how these factors add complexity to the task. It is also missing whether these factors are related/interdependent or independent.

Bonner (1994) classified elements of task complexity into three types: input, processing, and output. Each of them have two dimensions: the amount of information and clarity of information. Each dimension has different factors affecting complexity of the elements (input, process and output). Bonner's model is simple and easy to understand. However, it does not explain what the relationships among factors are or how these factors affect the overall task complexity.

To summarise, the methodology studying human factors and task complexity is adapted to offer useful information to inform automation design. The understanding of human skills and performance should be transferred to the product or process characteristics and requirements.

3 METHODOLOGY

This paper describes an industrial case study of a grinding and polishing process for high-end metal components. The aim of the study is to identify key variability within a manual process to produce products within the specifications. Inherent human disparity due to experience in the process object of study is considered but is not within the scope of this paper. The influence of the expertise factor is minimised through the selection of experts, although it is recognised that these workers may adopt different strategies to optimise their work output.

First, the main sources of variability in machines, materials, procedures and measurements are identified. The information was gathered from company documentation of product requirement, equipment, Standard Operating Procedures (SOP), supplier, quality and maintenance reports, customers' reports and warranty data.

Next, observations were performed whilst the operators perform their tasks. Observation has been shown to be a powerful tool for studying manufacturing environments and its variations, related to processes or workers: workers performance's variations (Fletcher et al. 2006), selection of variability for quality purposes (Thornton 2000), identification of sources of variability (Loose et al. 2008) and human error in complex environments (Rasmussen 1988). There are different ways of using observation as a research method (Slack et al. 2001). In this research, a non-participant (the observer stands at a distance from the process being observed), direct (the researcher observes and takes notes in the facilities), overt (the observed knows that the researcher is watching) and structured observation (structured observation requires some previous research from the observer in order to delimit what is important to observe).

Structured observation was chosen as it the most suitable for the environment and the nature of the tasks observed.
The processes were video recorded for further analysis and additional notes were made during the observation. Written consent was obtained from the participants and a brief explanation of the aim of the study and the process to be followed was provided verbally.
After the observation of the expert operators performing the tasks, they were interviewed. In this study the interviews were semi-structured, using a mix of closed and open questions. The interview process allowed the researcher to confirm quantifiable data (i.e. years of experience, tools used, number of pieces per batch) and to clarify some findings from the observations. The questions were subdivided into three categories: work experience, procedure and tools. Open questions were used to explore qualitative information related to the operators' ideas and experiences.
Three operators were observed and interviewed, all with extensive experience executing the process. A summary of the interviews is given in Section 5 (results). In addition, there are an inspection team which visually inspect every part processed. The four members of the inspection team were also interviewed to further investigate possible differences among the parts processed and their relations with the operator who processed them.
From the data collected and observations, the process was decomposed into key tasks and subtasks. By decomposing the process, it is possible to determine in which specific task the variability is introduced into the process and how the operator is accommodating for this variability. The process is represented using an IDEF0 diagram. The IDEF family models different views of a system. In the case of IDEF0 (U.S. Department of Commerce 1993) produces a structured function model to gain understanding, support analysis, provide logic for potential changes, specify requirements, or support systems level design and integration activities. An IDEF0 diagram describes what a system does, what controls it, what things it works on, what means it utilises to execute its functions, and what it delivers. The components in the IDEF0 are: inputs (I), controls (C), outputs (O) and mechanisms (M). Input data or objects are transformed by the function to produce the output. A control is utilised to address the work in the process. Plans, standards and checklists are all forms of control. Mechanisms can be staff, tools or equipment employed to carry out a task.
Finally, the Key Characteristics (KC) in Variation Risk Management is used to link the process variability identified to the product requirements (Thornton 2004). This method has been proven efficient in manual manufacturing processes such as automotive and aeronautic assembly processes (Thornton 1999a; Thornton 1999b). Different KCs can be found in a manufacturing process, for example in the components (dimensions, positions of holes and threads, material density, strength, roughness and elasticity), in the machines (e.g. configuration, data input, energy input, condition and age), tools (condition, use and shape) and environmental (lighting, temperature, moisture, noise and vibration). These KCs are identified from the previous stages (IDEF0 model).

4 CASE STUDY: GRINDING AND POLISHING PROCESS

The case study company is fully dedicated to providing component finishing services to aerospace and power generation industries. Their specialist capabilities and production processes are accredited for these specific industries to international quality standards. Their workforce is paid by part finished to specification; the rate paid varies, depending on the complexity of the part being processed. The company is interested in exploring how some aspects of the processes may be automated due to concerns for health and safety as well as difficulty in training skilled workers.

4.1 Process descriptions

The purpose of the finishing processes is to achieve a smooth transition or flow among the surfaces on each component. The material removed in finishing processes has to be kept to a minimum and the components' form should not be modified significantly from its original geometry. The flow among surfaces is critical to the functionality of the components. The process of grinding consists on removing a minimal amount of material from the surface of the component using a rotational tool spinning at high speed (2800 rpm and above). The grinding processes are used to improve the dimensional precision with respect to that obtained from machining processes, for example turning or milling. The polishing process consists of removing tiny particles from a surface to achieve a smooth surface profile. This smoothness is obtained by rubbing the surface against the polishing wheel using a rotational tool spinning at high

speed (2800 rpm and above). Polishing is used to generate surfaces with high tolerances in geometry, surface texture, and roughness.
Each work-cell has a double-ended polishing machine, equipped with an extractor, a lamp and a table where tools (wheel tools, sharpening tools and other tools) are placed. The configuration of the work-cell is shown in Figure 1.

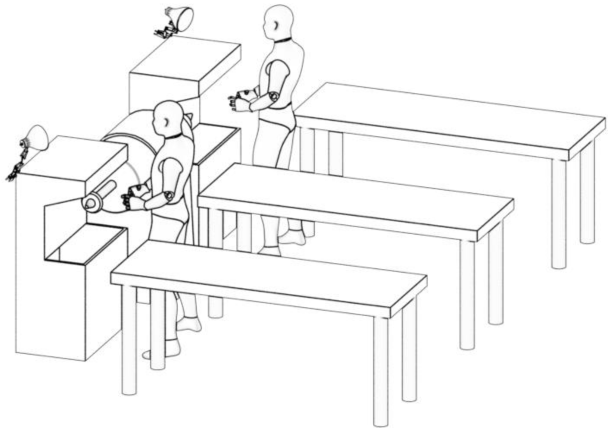

Figure 1. Working cell set up

The company works on a wide range of components for their customers. The components are semi-finished components coming from a casting process and hence, requiring surface finishing. When the finishing processes are completed, the components are shipped back to the customers to be assembled.
This case study focused specifically on a component. This component is the most complex component processed in the factory. The work is carried out by experienced and highly skilled workers who have to perform a long procedure (10 minutes per part on average) in order to present a finished product. The whole process is completed by one operator. Only a few operators (three at the time of writing) are capable to work on this part in the factory due to its complexity but, because it has a low demand (48 parts per day), it is not critical to the workload estimations. The component contains 5 main features including a number of 3D curvatures, fillet radii and protrusions. The components received from their customers for this specific process are in their final geometrical dimensions. A maximum deviation of ±100 µm from nominal is allowed in certain points, keeping a maximum deviation of ±50 µm or smaller for most of them.
A component with some similar features to the one studied is shown in Figure 2 in an attempt to illustrate the component's complexity, as the actual component studied cannot be illustrated due to confidentiality. There are six different features (including fin, platform, and fillet radii) that must be worked on but all of them are processed using the same techniques and principles.

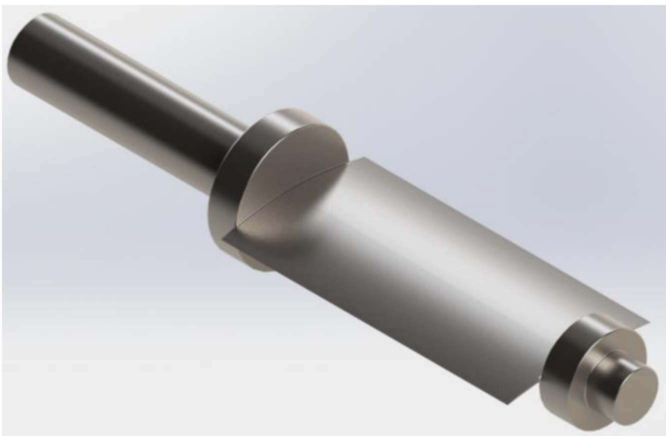

Figure 2. Representation of a complex component with similar features to the one studied (fin is not illustrated)

5 RESULTS

In this section the results obtained from the case study are presented. The analysis of the data collected through the case study; company documentation, observations, interviews, process model and key characteristics identification are explained below. Table 1 shows a summary of the questions and the operators' answers in the post-observation interviews.

Table 1. Post Observation Interviews

Question	Operator 1	Operator 2	Operator 3
Years working in the company?	22	19	13
Years working with this type of component?	More than 20	9	8
Do you notice differences between components?	Yes. Surface Finish	No	No
Do you notice differences between batches?	No	Surface Finish	No
How do you cope with these differences?	I spend time eliminating the mark and I report to quality	I spend time eliminating the mark	I always proceed in the same way, with all the parts
What do you control when you are performing the task?	Flow between surfaces and radii	Flow between surfaces, radii and dimensions	N/A
How often do you check the component?	All the time	All the time	All the time
Do you notice when wheel tool is degraded (wear in tool)?	Yes	Yes	Yes
How often?	Depending on tool	Depending on tool	Depending on tool
Do you work differently when you feel degradation in the tool? What do you change?	Yes, I apply more pressure and I keep processing for longer time	Yes, I keep processing for longer time and I change the tool	Yes, I apply more pressure, I keep processing for longer time and I change the tool
Who prepare and recondition the tools?	I do	I do	I do
Do you customize your tools?	Yes	Yes	Yes
What do you focus on when customizing?	Sharpness and Edge's Shape	Edge's Shape	Edge's Shape
What do you think are the main sources of variation?	Parts	Parts	Don't Know
What do you think is the most critical to comply with customer's standards?	Parts	Parts	Don't Know
How do you think this variation could be reduced / eliminate?	Improving prior processes	Don't Know	Don't Know
How do you think your job could be improved?	Reducing Vibrations	Don't Know	Don't Know

Based on the observation, an IDEF0 diagram for the grind and polish stage of the overall process is presented in Figure 3.

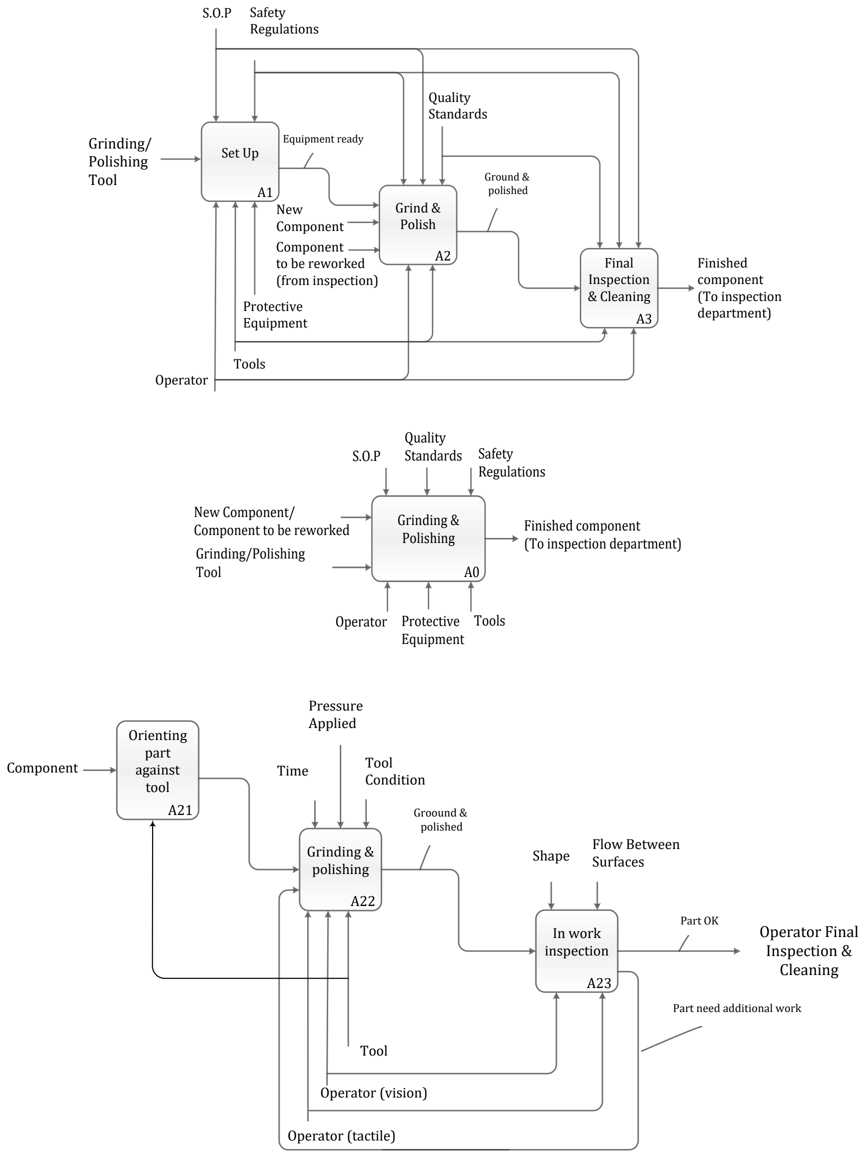

Figure 3. IDEF0 Diagram from process. A0 and A2 Level (only A2 is presented due to space constraint, all Controls apply to A21, A22 and A23; SOP and Quality Standards have been specialised further)

The main variabilities identified in the process are:

1. The time the operator spends grinding or polishing a specific feature on the component varies depending on the feature dimensions, pressure applied in the operation and tool condition.
   - If more material needs to be removed (due to variability in semi-finished part), then more time is required for grinding/polishing if other parameters stay constant.
   - Pressure applied changes the rate the material removed but higher pressure applied introduces vibration and degrades the tool more quickly.
   - Tool condition and shape affects the rate of material removed. When the tool has been recently sharpened, the tool grinds/polishes more efficiently. The operators customise their own tools to different shape.
2. The pressure applied by the operator is directly related to time of operation, vibration in the machine's axis, feature dimensions and tool condition.
   - Time of operation. If the pressure is not enough, the time spent in the operation will increase. If the pressure is too large, the operator will not be able to control the amount of material being removed; therefore, the component may be rejected.

- Dimensions of the feature. The correct pressure applied will lead to a more accurate amount of material removed, hence complying with the dimensional requirements of the features. The dimension of features varies from part to part.
- Vibration. When the pressure applied increases, there is more vibration in the machine axis making it more difficult to control.

3. The shape and surface roughness of the tool is directly controlled by the operator as they recondition and sharpen their own tools.
   - Pressure. The closer the tool is to its original shape and properties, the less pressure needs to be applied.
   - Tool wear. The condition of the tools and rate of tool wear depends on the way the operator works, parts requirements and the properties of the materials used.

The variabilities i.e. process Key Characteristics are interdependent and the operators need to manage these interactions dynamically to achieve an optimum outcome in terms of the specifications and their own motivation. Therefore, the operators are constantly controlling the pressure applied, grinding time, and tool conditions (shape and surface roughness) to meet the part requirements.

It was found that the operators generally followed the Standard Operational Procedures (SOP) but each of them added their own signature, meaning that they might vary the procedure slightly, for example by varying the sequence of actions. This was corroborated by visual inspection staff, as they can differentiate which operator has worked on the component by how it was ‘signed’. For example,

"I know who processed the part by the marks left in the part, it is like a signature" [inspection staff 3]
"I notice that different operators have different ways of proceeding" [inspection staff 4]
"Same errors are repeated by same operator" [inspection staff 3]
"You can see same differences over and over again" [inspection staff 4]

The different procedures adopted by workers have no impact on the final output, i.e. the components are equally acceptable at the end of the process. It is noted that process rework rate can be affected by the strategies adopted by the workers, but they are responsible for finishing their own parts to the required standard. Measurement data and quality reports from the customers showed that parts delivered by the operators do comply with the customers' standards. The customers have not reported any significant quality issue with the parts delivered recently.

In order to successfully cope with variability, the operators used their vision and tactile cues as well as rules and skills to act on those cues. The observations and interviews suggest that they have some awareness of dealing with variability (although not always recognised by the operators) but they act with unconscious control and automated behaviours (Rasmussen 1983). For example,

"I notice differences in surface finish among parts…" [operators 2 & 3]
"When tool starts degrading, I apply more pressure and keep grinding for longer…" [operators 2 & 3]

This was also verified through observation of operators where rapid movements and decisions are made with limited control or conscious attention following a stored rule, i.e. learning by training. This was corroborated by the answers in the interviews where generic guidelines, more like a ‘philosophy’ rather than a working procedure for the process were described by the operators. For example,

"I always proceed in the same way, with all the parts" [operator 1]
"I control flow between surfaces and shape…" [operators 2 & 3]
"I check my work all the time…" [operators 1, 2 & 3]

Figure 4 shows how the grinding/polishing KCs relate to the outcome Key Characteristics of the part. The process Key Characteristics identified in this case study are: time, pressure applied and tool condition (shape and surface roughness).

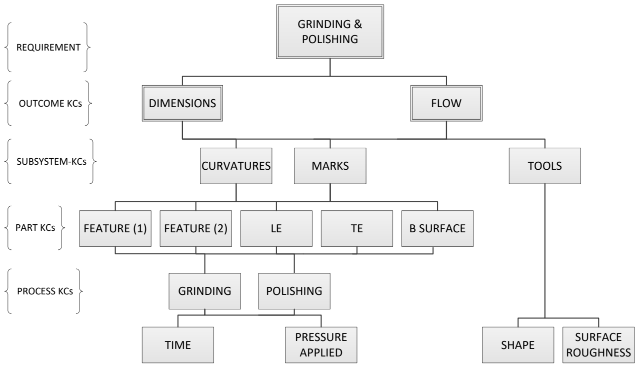

Figure 4. Key Characteristics (KCs) diagram (LE-leading edge, TE-trailing edge)

6 CONCLUSIONS

From the study of an industrial process on grinding and polishing, it can be seen that the operators are dealing with different sources of variability which are interdependent and those relationships change over time. This implies a challenging environment but the operators are adapting successfully to process variability due to their skills and experience. From a final product point of view, it can be said that workers are delivering outcomes which comply with the quality standards required. However, it was also found that procedures used by different operators may differ slightly.

Much work in ergonomics and human factors has been performed for understanding the properties of human capability without necessarily addressing how to translate this knowledge to inform industrial automation design. Based on the study of process variability, a methodology to link the product requirements to process KCs of a manual process is proposed in this paper. The interdependency of the different Key Characteristics should be taken into consideration when an automated solution is designed and human knowledge must be considered as an important asset. However, the operators are mostly acting with an unconscious and automated behaviour meaning that the procedures executed are embedded in their minds. In addition, it was found that some of the operations were performed by a stored rule meaning that operators follow a sequence of actions when they face a familiar work situation. This 'rule' may have been gained from experience, taught by others or was developed by a problem solving process (Rasmussen 1983).

In order to successfully automate the process, the automated solution should be in control and be able respond to process variabilities in real time. For the grinding and polishing case study, the automated solution should be capable of monitoring wear of the tool, measuring tool deterioration and adapting to this deterioration by changing pressure applied and time of operation to avoid any damage in the parts as this product is a high-value component. Further work will extend the framework to support the intelligent automation design to determine the required automation complexity once process variabilities are understood.

REFERENCES

Antony, J., Hughes, M. & Kaye, M., (1999), "Reducing manufacturing process variability using experimental design technique: a case study", *Integrated Manufacturing Systems*, 10(3), pp.162–170.

Apley, D.W. & Shi, J., (2001), "A Factor-Analysis Method for Diagnosing Variability in Mulitvariate Manufacturing Processes", *Technometrics*, 43(1), pp.84–95.

Bell, D.J. & Ruthven, I., (2004), "Searcher 's Assessments of Task Complexity for Web Searching", In *Advances in Information Retrieval*. Springer Berlin Heidelberg, pp. 57–71.

Bonner, S.E., (1994), "A model of the effects of audit task complexity", *Accounting Organizations and Society*, 19(3), pp.213–234.

Boot, W.R. et al., (2010), "Transfer of skill engendered by complex task training under conditions of variable priority", *Acta psychologica*, 135(3), pp.349–357.

Campbell, D., (1988). Task Complexity: "A Review and Analysis", *The Academy of Management Review*, 13(1), pp.40–52.

Carey, J. & Kacmar, C., (1997), "The Impact of Communication Mode and Task Complexity on Small Group Performance and Member Satisfaction", *Computers in Human Behavior*, 13(1), pp.23–49.

Dai, W. & Yang, J., (2011), "Decision-making in process design based on failure knowledge", In: *IEEE*

International Conference on Industrial Engineering and Engineering Management. Ieee, pp. 1505–1509.

Fletcher, S. R., Baines, T. S. & Harrison, D. K., (2006). An investigation of production workers' performance variations and the potential impact of attitudes. *The International Journal of Advanced Manufacturing Technology*, 35(11–12), pp.1113–1123. Available at: http://link.springer.com/10.1007/s00170-006-0793-y (Accessed May 7, 2013).

Glodek, M. et al., (2006), "Process Robustness", *Pharmaceutical Engineering (Online Exclusive)*, 26(6), pp.1–11.

Greitzer, F. L., 2005. "Toward the development of cognitive task difficulty metrics to support intelligence analysis research", In: *Fourth IEEE Conference on Cognitive Informatics*. pp. 315–320.

Klein, G. et al., (1996), "Decision Making in Complex Naval Command-and-Control Environments", *The Journal of the Human Factors and Ergonomics Society*, 38, pp.220–231.

Liu, P. & Li, Z., (2012), "Task complexity. A review and conceptualization framework", *International Journal of Industrial Ergonomics*, 42(6), pp.553–568.

Loose, J., Zhou, S. & Ceglarek, D., (2008), "Variation Source Identification in Manufacturing Processes Based on Relational Measurements of Key Product Characteristics", *Journal of Manufacturing Science and Engineering*, 130(3).

MacDonald, W., (2003), "The Impact of Job Demands and Workload on Stress and Fatigue", *Australian Psychologist*, 38(2), pp.102–117.

Montgomery, D., (2008). *Introduction to Statistical Quality Control*, John Wiley & Sons.

National Institute of Standards and Technology, 2016. e-Handbook of Statistical Methods. [online] Available at: http://www.itl.nist.gov/div898/handbook/ppc/section1/ppc132.htm (Accessed April 17, 2016).

Nembhard, D. A. & Osothsilp, N., (2002), "Task complexity effects on between-individual learning-forgetting variability", *International Journal of Industrial Ergonomics*, 29(5), pp.297–306.

Rasmussen, J., (1988), "Human error mechanisms in complex work environments", *Reliability Engineering & System Safety*, 22(1–4), pp.155–167.

Rasmussen, J., (1983), "Skill, rules and knowledge: Signals, signs, and symbols, and other distinctions in human performance models", *IEEE Transactions on Systems, Man, and Cybernetics*, (3), pp.257–266.

Sandom, C. & Harvey, R., (2004). *Human Factors for Engineers*, London : Institution of Electrical Engineers.

Slack, F. et al., (2000), "Observation : Perspectives on Research Methodologies for Leisure Managers", *Management Research News*, 24, pp.35–42.

Thornton, A., (1999a), "A Mathematical Framework for the Key Characteristic Process", *Research in Engineering Design*, 11(3), pp.145–157.

Thornton, A., (2000), "Quantitative Selection of Variation Reduction Plans", *Journal of Mechanical Design*, 122(2), pp.185–193.

Thornton, A., (2004). *Variation Risk Management: focusing quality improvements in product development and production*, John Wiley & Sons.

Thornton, A., (1999b), "Variation Risk Management Using Modelling and Simulation", *Journal of Mechanical Design*, 121(2), pp.297–304.

Thornton, A., Donnelly, S. & Ertan, B., (2000), "More than Just Robust Design: Why Product Development Organizations Still Contend with Variation and its Impact on Quality", *Research in Engineering Design*, 12(3), pp.127–143.

U.S. Department of Commerce, (1993). FIPS PUB 183: Integration Definition for Function Modeling (IDEF0). , p.120.

Williams, T.M., (1999), "The need for new paradigms for complex projects", *International Journal of Project Management*, 17(5), pp.269–273.

Wood, R.. E., Mento, A.. J. & Locke, E.A., (1987), "Task complexity as a moderator of goal effects: A meta-analysis", *Journal of Applied Psychology*, 72(3), pp.416–425.

Wood, R.E., (1986), "Task complexity: Definition of the Construct", *Organizational Behavior And Human Decision Processes*, 37(1), pp.60–82.

Xiao, Y. et al., (1996), "Task Complexity in Emergency Medical Care and Its Implications for Team Coordination", *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 38(4), pp.636–645.

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