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The application of Lean Six Sigma to the configuration control in Intel's manufacturing R&D environment

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Abstract

Purpose – The purpose of this paper is to provide an example of Lean Six Sigma (LSS) application in research and development (R&D) organizations to eliminate waste and improve systems based on available data that in turn improves the innovative environment. Manufacturing R&D involves designing and testing innovative concepts and taking them into high-volume manufacturing. The infrastructure associated with such organizations involves experimental manufacturing lines with the ability to evaluate the result under statistical process control and configuration control. The integration of LSS process improvement methodology into the R&D organization infrastructure and operations can have a dramatic effect on reducing cost and time related to the development and delivery of new technologies and products.

Design/methodology/approach – The LSS methodology was systematically implemented to eliminate waste and improve the existing process of Intel's configuration control during the development and ramp phases. The steps included an assessment of the current state through walking the process and collecting baseline data, preparing the process map to quantify waste and inefficiencies, defining the ideal state along with a realistic target, selecting and implementing the improvement actions together with realizing and documenting the improvements and finally developing and putting into place a control plan to ensure the new process is sustained. The LSS approach resulted in an efficiency improvement exceeding the target, i.e. 60 per cent reduction in idle time and waste (non-value-added activities) versus a target of 40 per cent reduction. The results also showed an increase in the stakeholder satisfaction without compromising the technical rigor of the manufacturing configuration control.

Findings – The LSS case study presented in this paper provides experiences to LSS practitioners in manufacturing R&D environment where the operational excellence is to be sought in new technology and product development.

Originality/value – Project leaders can use the study to help formulate strategies to cater to customer/stakeholder satisfaction and eliminate waste while maintaining the technical rigor of the R&D environment.

Keywords Six Sigma, DMAIC, Lean, Configuration control, Electronics manufacturing, Manufacturing research and development, Change control, Waste, Process efficiency, Project management

Paper type Case study

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1. Introduction

Lean-Six-Sigma (LSS) approach combines the benefits of Six Sigma method with the waste reduction philosophy of LEAN engineering (Arnheiter and Maleyeff, 2005). The LSS has become a popular tool to improve operational excellence in manufacturing (George, 2002; Liker, 2004) and other fields (Pojasec, 2003; Koning *et al.*, 2006; Guarraia and Schwedel, 2006; Herbert, 2008). Although traditionally the LSS has been implemented in improving systems in the high-volume manufacturing environment (George, 2002; Liker, 2004), its use has also been described in driving innovation in environments including the research and development (R&D) of several Fortune 500 companies (George *et al.*, 2007; Hoerl and Gardner, 2010; Carleysmith *et al.*, 2009; Barnhart, 2008; Rao). Although some have argued in popular media that process-focused methodology like LSS can potentially harm creativity and innovation (Ashkenas, 2012; Hindo, 2007), data exist to the contrary (Carleysmith *et al.*, 2009; Barnhart, 2008; Rao), especially if LSS principles are applied in R&D environments where "business processes" are improved to free the time for innovators to "think and be creative". Further, the LSS implementation though DMAIC (Define-Measure-Analyze-Improve-Control) methodology is highly effective in transactional environment (Antony *et al.*, 2012; Lee *et al.*, 2013), in healthcare (Gijo and Antony, 2013), in high-volume manufacturing (Habidin and Yusof, 2013; Jirasukprasert *et al.*, 2014), in education (Kanigolla *et al.*, 2014) and in general problem solving using R&D (Hoerl and Gardner, 2010; De Mast and Lokkerbol, 2012).

Intel designs and manufactures microprocessor chips used for different applications including servers, personal computers, mobile devices and embedded systems (Intel Technology Journal, available at: http://noggin.intel.com/technical-articles). Design-For-Manufacturing principles are used to implement manufacturing processes to meet design targets and design features that are manufacture-able in high-volume (HVM) environment. The necessity to develop HVM-capable processes requires the merger of statistical process control, configuration control (also called change control), etc., into the R&D environment. The configuration control during R&D represents a structure and means to assess risk, collect data and track and document the changes to the complex manufacturing methods used to create micro- and nano-scale features of the processors (Intel Technology Journal, available at: http://noggin.intel.com/technical-articles). In this paper, we present a case study of successful implementation of LSS to the configuration control process in the R&D environment. Idle processes were eliminated and standardization was adopted in the "business processes" associated with the manufacturing configuration control. The steps included an assessment of the current state through walking the process and collecting baseline data, preparing the process maps to quantify waste and inefficiencies, defining the ideal state along with a realistic target, selecting and implementing the improvement actions together with realizing and documenting the improvements and finally developing and putting into place a control plan to ensure the new process is sustained. The project resulted in efficiency improvements exceeding the target, i.e. 60 per cent reduction in idle time versus a target of 40 per cent reduction. The results also showed that the stakeholder satisfaction increased without compromising the technical rigor of developing micro- and nano-scale manufacturing processes.

2. Business case

Before describing the details of the LSS implementation, it is worth mentioning the importance of configuration control process in the R&D environment. The configuration control is necessary for continuous learning, such that all the issues/technical contents are properly documented so as to be used by the next generations of engineers facing similar technical challenges for future technologies. Further, the configuration control facilitates sound decision making based on statistical data collection and technical risk assessments rather than "split of a second" decisions based on impulses that work only in special circumstances. Considering the complexity of the micro- and nano-scale manufacturing process steps, a robust configuration control process is a necessary condition for successful R&D that leads to high-tech manufacturing. Any improvements to the business process of configuration control can thus bring in not only stakeholder satisfaction but also real benefit to the company in terms of the robustness in technical decision making and database management. Thus improving the business process of configuration control through LSS was to result in cost savings from a reduced number of defects, time savings for R&D engineers from elimination of non-value-added (NVA) activities that far exceeded the cost of quality improvement.

The then "current state" of the configuration control was highly bureaucratic with pre-review members and multiple configuration control board review meetings. The process had evolved to enable multiple checks and balances at the expense of the White Paper (WP) process times and long wait times for authors. In other words, the authors dreaded the "process" part of the configuration control more than the technical aspects. Further, we found that there was no feedback mechanism to improve the quality of WPs; with repeat offenders being responsible for bottom 10 per cent WPs. Combined with the importance of the configuration control and the stakeholder perception of the process, a strong business case could be made for the implementation of LSS principles to reduce waste and improve efficiency.

3. Methods

We will describe the LSS DMAIC framework implementation in this section with subsections for each of the phases. The data will be normalized due to company confidentiality. The action items to implement the LSS are summarized in Figure 1 (Lean Six Sigma training manual, 2013).

Lean / Six Sigma	Principle One: Directly observe work as activators, connections and Flow	Principle Two: Systematic waste elimination	Principle Three: Establish High Agreement	Principle Four: Systematic Problem Solving	Principle Five: Create a Learning Organization
Define (D)	Process Flow	SIPOC, VOC	Project Charter, VOC, Pareto	Multi Level Pareto	Business Process Management Tollgates, Project Reviews, Forums Learn, Apply, Reflect
Measure (M)	Process Map, Operational Definitions	Process Map, 5 Ways, Value Added Assessment	Cause & Effect	MSA, Process Capability	
Analyze (A)	Data Integrity, Multi-Variation	Hypothesis Testing	Cause & Effect/Stability	FMEA, Regression	
Improve (I)	Updated Process Map	Solution Selection	Solution Selection	DOE, TRIZ/ASIT	
Control (C)	Pilot Solution	Control Chart Action Plan	Control Plan	Solution Sustain	

Figure 1.
Principles of Lean and Six Sigma applied for business process improvement (Lean Six Sigma training manual, 2013)

3.1 Define

An LSS team was formed with the authors as its members. Each member was part of the DMAIC tasks. Formation of such a small team of empowered R&D engineers at the point of the process steps is typical in the LSS methodology and provides the required inputs to be gathered to improve the process. A time span[1] was assigned to complete the DMAIC process, with the defined goal of 50 per cent reduction in idle wait time and a reduction in the process variability through:

- structured and standardized activities;
- clearly defined transfer through optimum connections;
- simple and specific process flow; and
- small and rapid improvements.

The team started with asking the process questions and to gather the voices of customers, business and the employees in the process (VOC, VOB and VOE) to understand the critical process steps for the WPs for the process changes. The process steps that did not need critical technical input were targeted for either significant reduction or outright elimination to achieve the target of the idle time elimination. In addition, the mandate to the team was to understand the "what is" state and the ideal state of "what should be" in terms of the business process.

The team started with defining the high-level process flow in the then "present" form (Figure 2) to help us define the process boundaries of the configuration control process we want to improve. There are two levels of review forums and team member approvals in the configuration control software system. The first thing to observe is that although the activities are standardized, they are not structured. For example, the same team members who write the change and provide inputs also approve the WP in the computer system. In a manufacturing R&D environment, this could be large numbers of

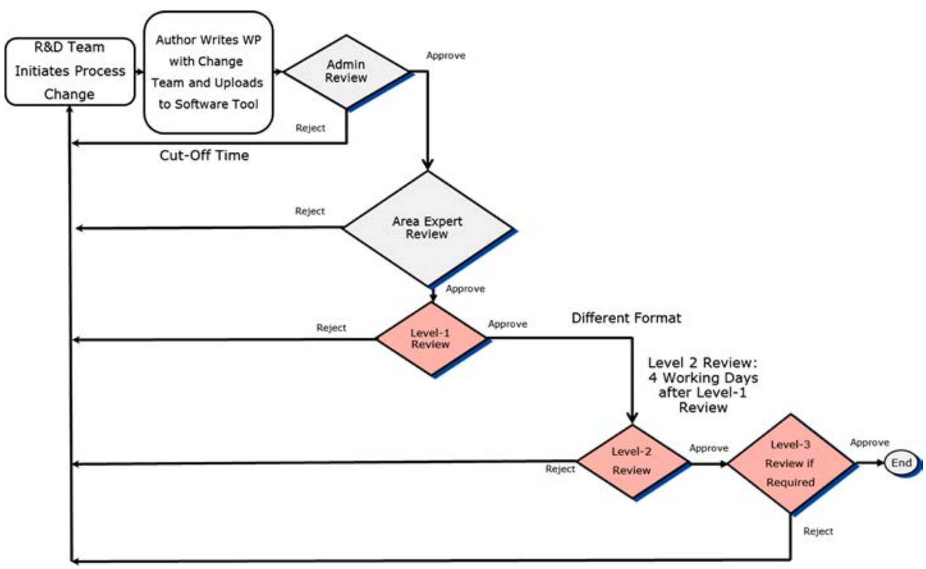

Figure 2.
High-level initial configuration control process flow

stakeholders ranging from finance to capacity to different technical areas such as mechanical engineering, materials science, physics, chemical engineering, applied mechanics, etc. Further, the flow is not simple for anyone wanting to change the process. The information transfer also included so many stakeholders so that the principle of "one customer, one supplier, one method of information transfer" was not followed. Also, the format of the WP was different for the two review levels, making it highly inconvenient for the authors. Finally, the team members linked the complexity of the process to the technical rigor – in other words, we did not realize that "Technical difficult problems can be solved using simple business processes"!

The SIPOC table (Supplier-Inputs-Process-Outputs-Customers) as shown in Figure 3 was used to identify the requirements from the customers (R&D team, factory, management and WP authors), the process inputs (software tool, WP template, change forums, etc.) together with the process requirements and suppliers. Following the SIPOC diagram, we collected baseline data from R&D engineers via a questionnaire to determine the time required for each step of the configuration control process, the level of their satisfaction with the current process and specific improvement ideas. This information provided valuable input for the estimation of the current WP process cycle and active time and was also used for our future state discussion.

3.2 Measure and analyze

The current state configuration control process map is shown in Figure 4. The process map consists of the micro steps of the change process and the required time per step. The NVA steps (pure waste) are shown in orange color. The NVA time was mainly from time spent by the engineer waiting for approvals from the subject matter experts. It is clear from the process map that we can clearly differentiate between idle time and active time. This idle time is exactly what needs to be quantified in order to be addressed to make the business process lean and reduce the variability. The quantification of value-added and NVA steps was done based on the data from the completed questionnaires by multiple WP authors. Some of the time spent on the WP is necessary for the technical discussions related to the changes, while some time is spent waiting for approvals and the time spent waiting in-between different levels of review. The team then discussed and categorized each of the process steps as "value added", "non-value added, but necessary" and "non-value added", where the NVA steps with the highest score were targeted for the improvement actions. The measure of time required for each of these processes is Intel confidential information – however, we provide the relative time spent for each of the processes as a measure of a time unit "t" (Figure 4). For example, if the time required to map out the experimental strategy is "2t", the time required to wait for acceptance from the stakeholders was "33t", the latter being an idle (i.e. noncritical) step.

The team utilized a prioritization matrix to match input from customers and generated the cause-and-effect matrix Pareto chart (Figure 5). Again, the relative times required are provided without affecting the purpose of the case study. We then considered the items from Figure 5 above an arbitrarily selected cutoff score and carried out their failure-modes-and-effects-analysis, i.e. FMEA. The FMEA is a common industry tool that lays out "what can fail" in a business process and analyzes the reasons behind the failures and the possible corrective actions. The Severity, Occurrence and Detectability numbers are chosen from past experience. A partial configuration control

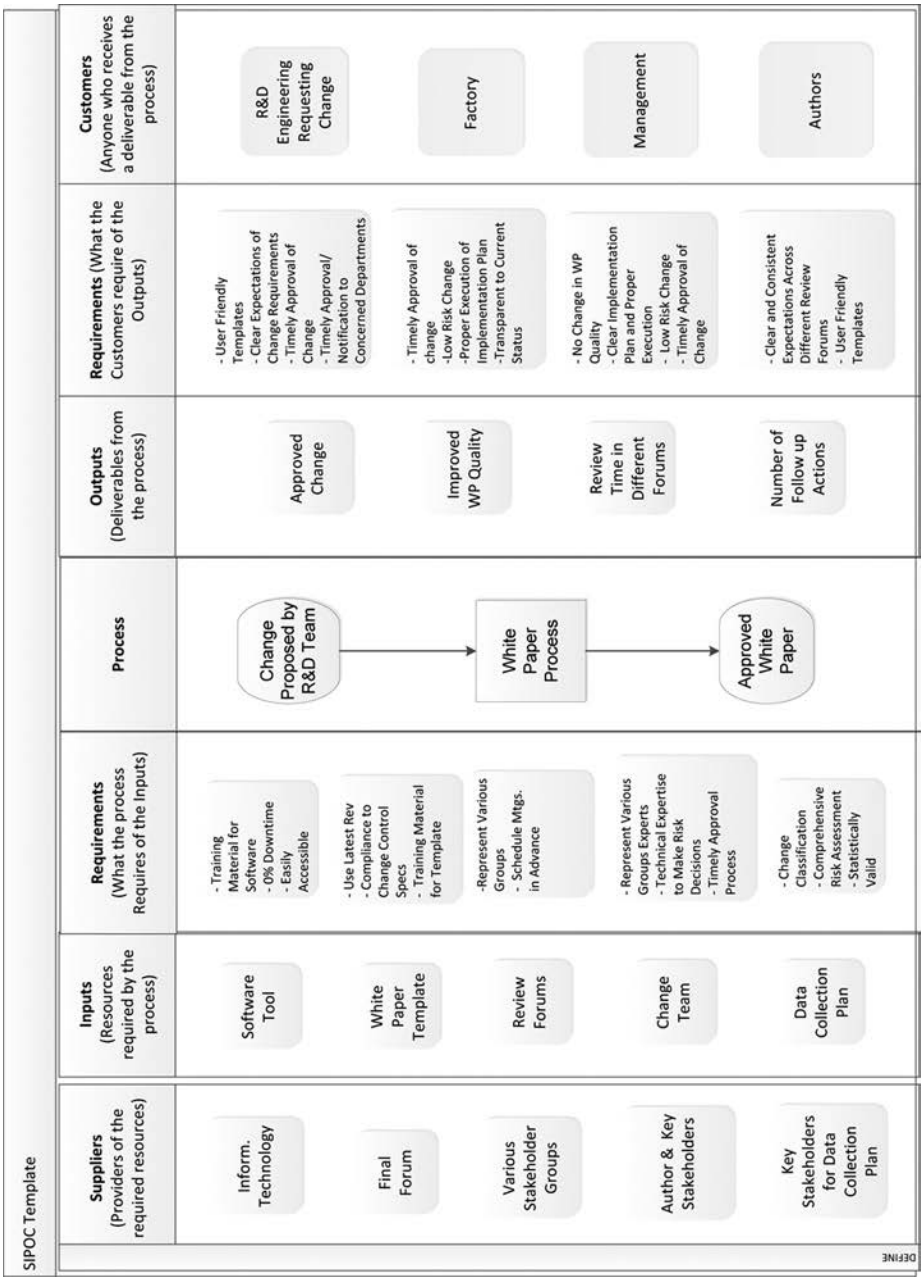

Figure 3.
SIPOC table for the manufacturing R&D configuration control

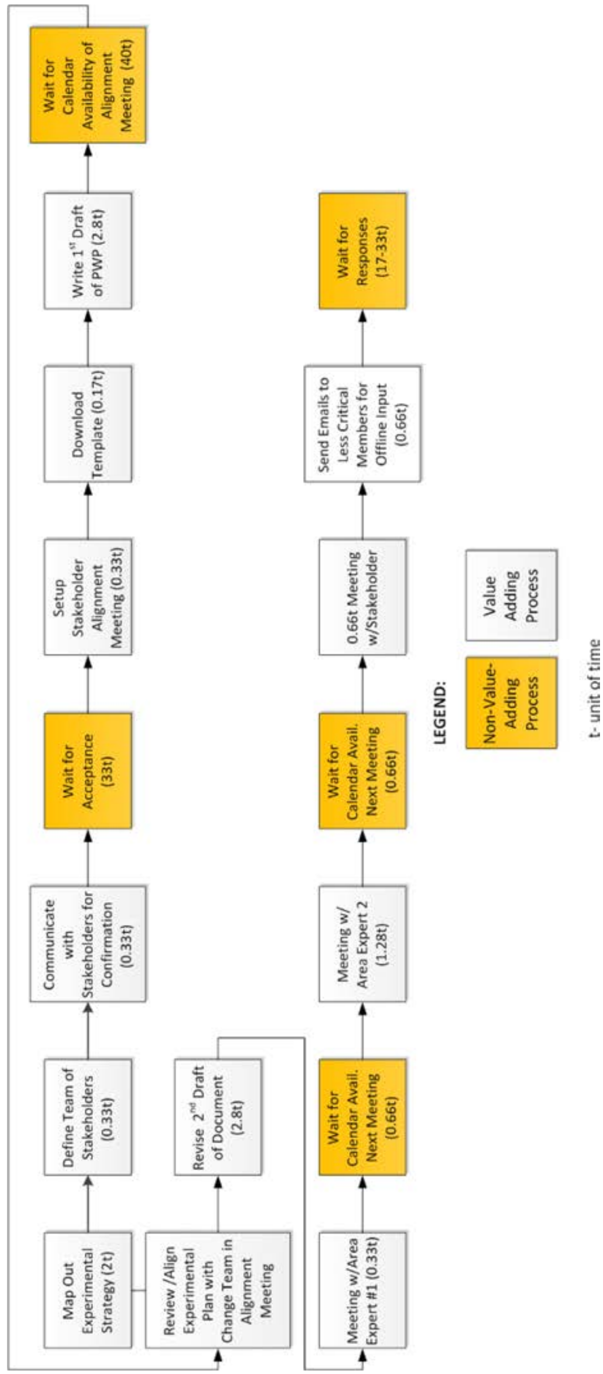

Figure 4.
Example of detailed process map for R&D engineers (not complete list) to go through the configuration control process

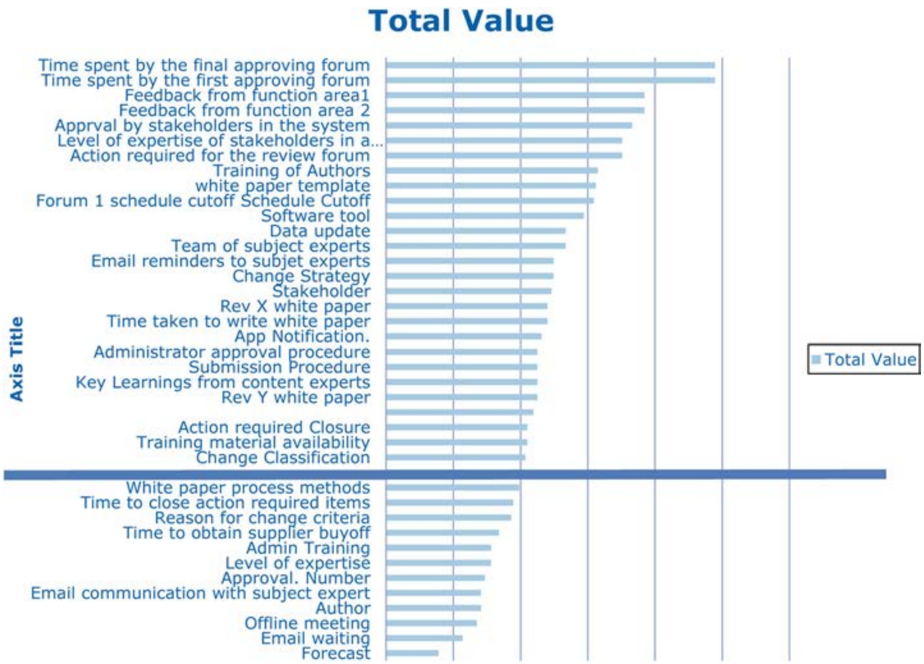

Figure 5.
Pareto chart describing "what is important for the customer" in improving the configuration control process. The chart is generated from direct customer feedback on the "customer requirements" of the SIPOC table for each of the process steps

FMEA is shown in Figure 6, with the actual numbers not shared due to company confidentiality. The Risk Priority Number (RPN) was then calculated by multiplying the occurrence, severity and detectability. Note that the actual numbers for severity, occurrence, detectability and RPN are not shared due to company confidentiality requirements. The team then concentrated on the highest RPN numbers to improve the business processes. The FMEA also helped the team brainstorm the solution paths for the issues identified in the analysis section.

The team identified the reasons behind the "as-is" condition. It was clear that without the critical steps of the LSS methodology, process deficiencies are not highlighted by the team members and they adhere to what is being done in the past. Further, we discovered in R&D teams that the technical difficulty was often confused with difficulty in process flow. The critical thinking induced by LSS helped change the "old habits" as described in the below "Improve" segment.

The team then discussed the ideal state and brainstormed improvement ideas to eliminate the NVA wait times and simplify the process flow. A simpler business process was expected to help the R&D team to concentrate on the technical aspects of electronic manufacturing rather than the business process.

3.3 Improve

FMEA was used to prioritize the improvement actions based on the higher RPN scores. The analysis of such cause-effect table resulted in having an arbitrary number; each of the process steps describing the impact of the process inputs on the customer requirements identified in SIPOC. An arbitrary cutoff was chosen; where items above

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEV	Potential Causes	OCC	Current Controls	DET	RPN	Actions Recommended	Resp.	Actions Taken	SEV	OCC	DET	RPN
Area expert* approval in software system	Area expert out of location	Delay in approval & implementation and missing		Sick, business travel		Human Dependent			The area experts need not provide explicit approval in the software system	Forum Chairs	Notify/train authors to work with area experts prior to submission, and set the experts as FYI in the software tool				
	Area experts do not approve on time			Some area experts have too many review requests, notifications may be missed		Email reminders, escalations - but dependent on case-by-case basis									
	Area experts do not carefully review change	White paper is rejected at different forums		Area expert not responsible for WP		No proactive controls, unless change is rejected, in which case author goes back to the area expert team			Periodic training for stakeholders	Forum Chair	Forum member to came up with suggestions				
		White paper is approved but gaps surface at customer		Area expert not qualified to give proper feedback					Feedback system/ Escalation path clearly defined						
									Recognition for change team members, based on author feedback		Positive feedback system for authors writing excellent white papers with sound inputs from area experts				
Additional Items															

* Areas of expertise can include sciences and engineering along with finance, business and other divisions

Figure 6.
Part of the configuration control failure modes and effects analysis (FMEA). The severity (SEV), occurrence (OCC), detection (DET) and RPN numbers are filled based on team's past experiences (actual numbers not shared due to company confidentiality requirements). The RPN numbers are calculated as SEV × OCC × DET

this level were targeted for improvement. The key item in this exercise was to come up with wait time versus time required for the change based on the process map created by walking the process. The corrective actions were intended to make the process flow simple, reduce idle time and waste and better control the output variability. Following action items were identified as corrective actions as described in Table I.

3.3.1 Not requiring the team of area experts to approve the change in the software system. This was a major improvement item, as it reduced the waiting time for the R&D engineer responsible for the manufacturing process change by 35 per cent. The area experts work with the owner of the process change in writing the WP. The approval in the software system by the area experts is thus a redundant activity that we were able to eliminate. This further simplified the initial process flow shown in Figure 2.

3.3.2 WP quality and content feedback for the technical change prior to review. The team added a new requirement of two-day prior feedback to the WP owners via the configuration control software system. The feedback covers the technical aspects (experimentation and simulations) and the WP quality of the change. Due to the global nature of R&D, the automated prior feedback helped facilitate the technical evaluations while reducing the communication time. We can thus use the "follow the sun" model. Another benefit of this corrective action was that the variation in the "human temper" of the members involved was minimized. The idle time reduction by this change was about 9 per cent of the total time required for the WP cycle.

3.3.3 Reduce the time difference between different levels of review forums. This corrective action had to balance between the time required by the reviewers, and the wait times of the change/WP owners. Reviewer feedback and author feedback was considered when reducing the time between the meetings. The reduction in wait times has helped the authors significantly in reducing the NVA time by 11 per cent.

3.3.4 Consolidation of technical area experts/groups. The process map showed that the change/WP owners spent several hours of time aligning with different members of the specific technical areas. Significant variation in technical recommendation was observed due to multiple inputs from the members of the same technical team. To reduce this variation, the team decided to assign a single point of contact for a given technical area for feedback to the change owner. For example, a single physicist was assigned to address all the physics-related aspects of the change to Intel's manufacturing process. This arrangement also facilitates cross-program learning. The reduction in NVA time was 4.5 per cent of the total time spent on WP cycle.

3.3.5 System to reduce WP quality variation. We then decided to create WP quality tracking sheets. Such a sheet ranked the changes in terms of a set rubric such as quality of clarity, technical content, risk assessment, evaluation plan and change implementation. Change owners with good score on this rubric were rewarded with recognition, while a mentoring system along with manager notification was put in place for those with poor scores. An immediate systemic improvement was observed with a sharp reduction in the "repeat offenders" seen prior to the corrective action.

3.3.6 Standardization of the WP templates. The team then worked with the automation teams in the company to create universal WP templates for technical changes across the organization. This simple improvement action significantly reduced the confusion among authors and reduced the variability in the business process. This

Table I.
Improvement action summary with risk and mitigation

#	Description	Risk	Risk mitigation	RPN from FMEA (> cutoff)	% Improvement in wait times
a	Make the team of area experts only as FYI in the software tool from present all approvals being mandatory	WPs go through the system without the required checks and balances; lack of "proof" that an area expert did or did not approve a WP	Reinforcement of roles and responsibilities in the organization; improve collaboration between the authors of the configuration control and the technical experts	1.8x	35
b	Provide feedback to authors two days prior to Level-1 review	None	NA	1.8x	9
c	Change gap between Level-1 review and Level-2 reviews to two days	Limited time for the committee to review WPs	Reinforcement of the changes to the committee members; limited risk, as VOC showed that the committee looks at the WPs a day prior to the review on average	1.08x	11
d	Consolidate # of groups/members per group to clarify WP R&R for each member	None	NA	x	4.5
e	Create white paper quality tracking sheets and mentoring system in place for any poorly scored white paper author	White paper authors may feel the system intimidating	Improved communication with the authors to positively reinforce the objective of improving the process and reduce variability	x	NA
f	Same format for all review forums	None	NA	x	0.5

helped reduce the number of reworks needed (due to incorrect template usage) and also reduced the time needed to write WPs. The estimated time savings was about 0.5 per cent of the total time required for the WP cycle.

The improvement results are quantified in Table I. The first action of making the team of area experts only as FYI in the software tool had the highest impact in terms of reducing the idle times. Note that a risk analysis was conducted by the team for each of the changes as shown in Table I. The risk mitigation required an organization-wide education and improving the collaboration between the authors of the configuration control technical experts. This was effectively done by presenting changes in relevant forums/meetings and developing a class that was delivered to the WP authors and area experts of the nano- and micro-scale manufacturing change control.

Through the above corrective action, the R&D configuration control process was greatly simplified. A new process map was then drawn with simper flow and clear connections (Figure 7). The direct result of these changes was multifold. First, the reduction of the idle time was achieved in the entire configuration control process that

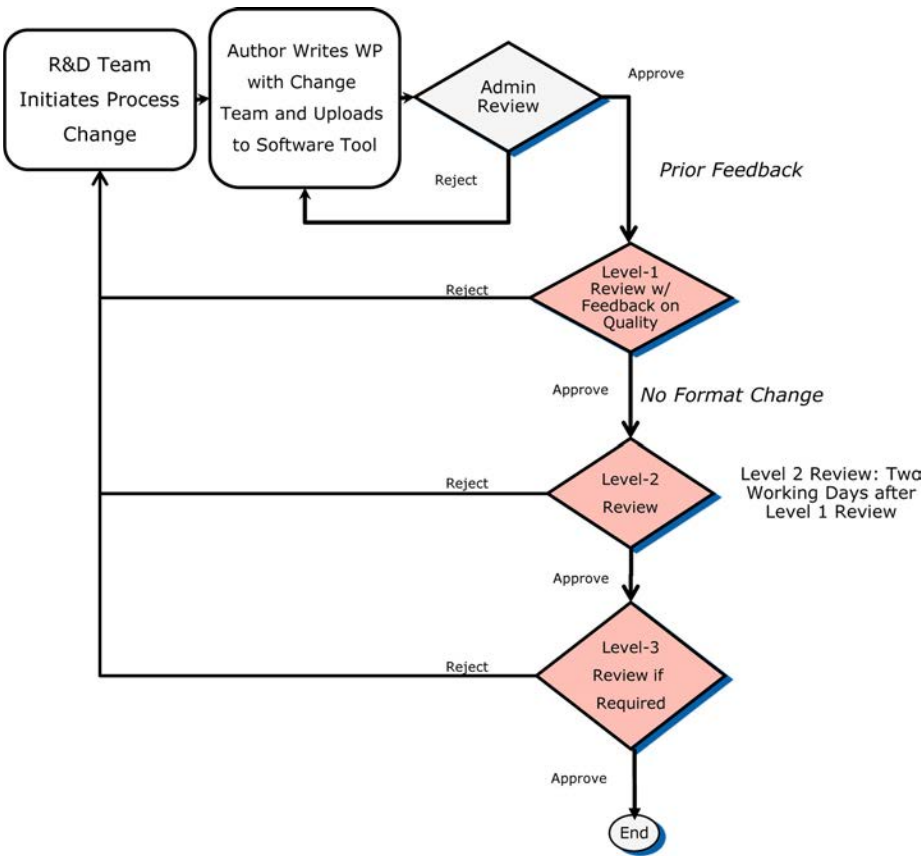

Figure 7.
Simplified configuration control process flow

exceeded the target state. The idle time per change item in manufacturing reduced by 60 per cent; freeing up the time of the R&D engineers into looking at technical aspects of the problems rather than the business process. This translated into significant cost savings for the company (not disclosed due to company confidentiality). Further, standardizations in the process reduced the variation, making the change process more predictable and efficient without reducing the technical rigors of the science and engineering of the micro and nano manufacturing problems.

3.4 Controls

All the changes mentioned above were then systematically downloaded to the R&D teams through a combination of training material and courses. Due to the large numbers of stakeholders for the configuration control process, several training sessions were carried out to reinforce the changes. Further, a requirement was made for all the R&D engineers who are first-time WP authors to take a class on the new configuration control process. Software tools were created to integrate the corrective actions stated in the Section 3.3 into a track-able system. Each functional area owners have been assigned to ensure smooth implementation and quick response in case the systems are down. Such controls have made the changes permanent, not requiring the human glue to continue their implementation. The results of the LSS implementation in terms of the WP quality score for technical content, the average time required to review the WPs, etc., were monitored continuously through the quality tracking sheet. In addition, the quality tracking sheet is expected to quantify the "current" state at any future time, thus making it easier to introduce measurable improvements.

4. Discussion

The present case study demonstrates that simple and rapid improvements through direct observations can improve the business processes considerably. Such a result has been achieved in the micro and nano manufacturing R&D environment. The time freed by these improvements was useful for the R&D engineers to think about research problems. Further, the quality feedback and mentoring system provided an excellent opportunity for new engineers to learn about the Intel configuration control business process. The two-day prior feedback also reduced the time spent by the review team to look at the preliminary and the final WPs. Finally, the quality tracking sheet provided a quantification of improvements during and after the entire configuration control process.

Figure 8 shows the effect of LSS implementation on the configuration control. The average time required per WP went down by about 50 per cent (Figure 8, left). This directly saved the time of the Level-1 and Level-2 review members and also the engineers owning the change. The decision making in the configuration control was also improved. The reduction in review time was most likely due to the second improvement (b), where technical feedback was given to the authors ahead of the forum review. This prepared the authors with all the questions in the review committee members. The Figure 8 (right) shows the quality of the WP in arbitrary units. The quality of the WP was determined by a rubric that considered the technical depth of the manufacturing change (e.g. if the authors know the physics/chemistry/engineering of the problem) and the structure of the planned evaluation and implementation. The feedback given to authors and the mentoring system improved the quality of the WPs by about 20 per cent (per the predetermined rubric). In addition, the reduction of 60 per cent in the time for preparing the WPs was confirmed by the authors through feedback.

The present case study highlights the completeness of the LSS methodology itself. The DMAIC framework complemented the waste reduction using lean principles. For example, the VOC established the process activities that needed improvement; while the cause-effect table and the FMEA created the exact action items that could be directly executed. In other words, the implementation of the LSS principles in Figure 1 automatically led to removing the inefficiencies in the systems and reducing the process variability. The small and rapid improvements through direct observations could then result in system efficiency improvement for manufacturing R&D and direct dollar savings for the company. Improved efficiency in R&D operations can help spur innovation benefiting the country and the society as a whole (May, 1997).

5. Conclusions

A case study is presented where the configuration control process of manufacturing R&D was systematically improved by the applying of the LSS methodology. Waste was eliminated by reducing the idle time experienced by the researchers and engineers who implement the change while reducing the business process variation simultaneously. The LSS steps included the systematic approach along with an assessment of the current state through walking the process, preparing the process map to quantify waste and inefficiencies, defining the ideal state along with a realistic target, implementing the improvement actions and finally realizing and documenting the improvements. The LSS approach resulted in an efficiency improvement exceeding the target, i.e. 60 per cent reduction in idle time and waste versus a target of 40 per cent reduction along with reduced business process variation. The results also showed an increase in the stakeholder satisfaction without compromising the technical rigor of the manufacturing configuration control.

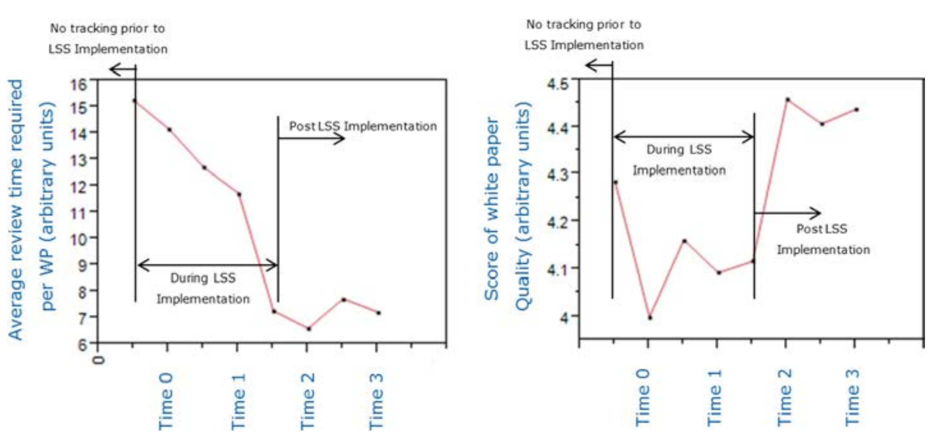

Figure 8.
Effect of the LSS implementation on average time to review changes (left) and the quality of the white papers (right). In both the cases, the improvements are clearly observed

Note

1. The time given to the team to reach the stated goal was of the order of several quarters. The exact time is company confidential information and hence cannot be disclosed.

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