INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED13
19-22 AUGUST 2013, SUNGKYUNKWAN UNIVERSITY, SEOUL, KOREA

TRACKING PRODUCTIVITY PATTERNS IN AN ENGINEERING DESIGN PROJECT

Anders BERGLUND, Johannes BLACKNE, Niklas JANSSON, Sofia RITZÉN
KTH Royal Institute of Technology, Sweden

ABSTRACT

This paper aims to analyze if self-evaluation of perceived productivity could help detect alarming patterns in time and stop projects from failing. The study is based on descriptive quantitative data that has been gathered continuously throughout a student engineering design project, highlighting three factors of influence; perceived productivity, perception of stage completion and work activity distribution. The productivity data was analyzed by detecting patterns in form of peaks or lows and combining the patterns with qualitative data from observations and documented work activities. Measurements were done on 33 occasions during the project where 280 individual answers for productivity (P) and completion (C) and 115 individual answers for work activity distribution were collected. The findings provide extraction of peak values and low values that enable tracking of critical incidents. Through an in-depth activity back-log each value was enriched with an understanding of what took place and its project consequences. Over time the recognized pattern helped the design team to become more proactive in activity precision and execution, resource allocation and process reflections.

Keywords: perceived productivity, pattern, completion, measure, engineering design project

Contact:
Anders Berglund
KTH Royal Institute of Technology
Machine Design
Stockholm
10044
Sweden
andersb5@kth.se

1 INTRODUCTION

Nowadays, engineering design projects are an institutionalised part of most universities' masters level programs. Although these projects seek to foster the pragmatic skills involved in establishing new products or services, little emphasis has been put on tracking the rollercoaster of activities that project members experience. This process perspective on what takes place allows for a deeper understanding in how resources are allocated and how perceived establishments are grasped and acted on in the project group. This paper presents a self-tracking method that promotes efficiency and detects problem areas for engineering designers as they engage in designing new innovative products. The paper discusses the impact of continuous self-evaluated productivity, the meaning of patterns detected, and what causes these patterns in an engineering design project.

Past studies have placed great attention on the importance and implications of project-based learning (e.g., de Graaf & Kolmos, 2007; Blumenfeld et al., 1991), yet have failed to pay similar attention to details that could strengthen the learning efficiency of such projects. In an overview of existing literature in the field of engineering education, we find that student engineering design projects rarely use productivity evaluations or similar process measurements. Self-evaluation is a form of self-efficacy, which is described as a measure of a person's own ability to complete tasks and to reach goals (Ormrod, 2006). This research used a continuous self-evaluation measure in the project context with the aim to detect concerning patterns and shine a light on critical areas in order to maintain high productivity and ultimately avoid project failures.

This offers a first step towards measuring success in student design engineering projects through continuous self-evaluation of productivity. Tracking also offers a way to understand blind-spot activities that influenced the project in certain directions but that were difficult to pinpoint. These activities were also often beyond the control of the instructor who served as a facilitating coach.

2 BACKGROUND

Insufficient planning and unrealistic project plans seem to be two major causes for time and cost overruns; estimates must be made taking several factors – such as productivity – into account (Bashir & Thomson, 1999). Past research indicates that there are no consistent methods to measure productivity (Ramírez & Nembhard, 2004). This means that there is a gap to fill in measuring and detecting patterns in self-evaluation of perceived productivity.

Productivity refers to the output of quality work, given a certain input; it is not a ratio between a quantity and a time unit. This study combines self-evaluation and productivity in the sense that the team members themselves evaluated how productive they felt the entire team was during the workday. Past research has shown that self-efficacy can give reliable results (Carbarry, Lee & Ohland, 2010).

There are two approaches to detecting patterns in self-evaluations of perceived productivity. The first is to look at long-term patterns and note whether change has occurred in productivity ratings over time. The second is to immediately detect and reflect on the last measurement date. Project teams can immediately analyse and discuss why, for instance, productivity was low the previous workday. Additionally, there are two ways to measure self-evaluation of perceived productivity: either by continuous measurement of perceived productivity (for example, on a daily basis) or by randomly sampling. Random sampling sets higher requirements on the implementation of the measurements and the reliability of the data.

Tracking or measuring productivity is not something new, and it has been studied in other fields besides engineering education, such as knowledge workers, R&D and engineering/business students. The application of metrics in design projects facilitates better follow-up and improved planning of upcoming projects (Xijuan, Yinglin & Shouwei, 2003). Measuring productivity could be beneficial by aiding in project monitoring, facilitating better project planning and helping set benchmarks (Ramírez & Nembhard, 2004; Brewer & Mendelson, 2003). Furthermore, self-assessment of team performance has a positive association with the project outcomes, as it strengthens the relationship between the importance of the process and the outcome-related nature of the project (Palmer & Busseri, 2000). Self-evaluations of productivity are said to improve the planning process and increase communication between team members (Shekar, 2007). Earlier attempts to look at this tool measured productivity through peer ratings; this approach has been considered more realistic in its accuracy and therefore better than other semi-quantitative methods (Pappas & Remer, 1985; Kim & Oh, 2002). Furthermore, Kim and Oh (2002) suggests that an ideal R&D performance measurement system evaluates both productivity and teamwork.

Peer evaluation can help detect and measure intangible data that would not be captured by other methods (Ramírez & Nembhard, 2004; Pappas & Remer, 1985). However, there are some issues with peer evaluation that must be taken into consideration when working with such measurements. First off, respondents tend to rate themselves higher than the rest of the group in such ratings (Pappas & Remer, 1985). Secondly, peers could receive a rating that is not only based on current performance but also on past achievements (Ramírez & Nembhard, 2004). Furthermore, it is important that peer evaluations are handled and administered properly to avoid creating the feeling among the group that they are being monitored and evaluated at all times by their peers (Pappas & Remer, 1985). Peer evaluation could, however, be superior to managerial evaluation when assessing individual performance in R&D projects (Kim & Oh, 2002).

We need further research in the area of metrics, productivity in R&D and project performance (Bashir & Thomson, 1999; Pappas & Remer, 1985; Ramírez & Nembhard, 2004; Karlsson, Trygg & Elfström, 2004). Tracking productivity in engineering design projects is one step in the right direction; further research on metrics in mechanical engineering projects may create better metrics and thus enhance project planning (Bashir & Thomson, 1999; Xijuan, Yinglin & Shouwei, 2003). Even though tracking team members' self-perceived productivity or other metrics (for example, peer evaluation) may involve subjective data, it is a step towards quantifying project and individual performance – key parameters in project planning and evaluation (Bashir & Thomson, 1999; Xijuan, Yinglin & Shouwei, 2003). This approach is superior to other productivity measurements if undertaken with care (Pappas & Remer, 1985; Kim & Oh, 2002).

Past research that looks at why projects scheduling and cost overruns occur suggests that it is important not to neglect the measurement of processes that could help improve it (Bashir & Thomson, 1999; Karlsson, Trygg & Elfström, 2004). Karlsson, Trygg and Elfström (2002: 179) state that "to make this increase in productivity possible, the productivity must be measured". Here we address the question of how to measure productivity, and how it influences project processes, through both immediate reflection and on an on-going basis, by visualising peaks and lows in productivity metrics.

3 METHODOLOGY

In order to work effectively and efficiently, a measurement system consisting of perceived productivity was implemented after the start of the project. To help detect patterns, additional measurements were introduced. Perception of stage completion and work activity distribution, with a focus on IT, was also implemented. The aim of this tracking was to identify critical patterns, reflect on the methods used and implement improvements. It became a way of "checking the temperature" of the project, allowing critical issues to be detected before they caused any major upsets.

The study was conducted both qualitatively and quantitatively using a 'productivity and completion poll' after each workday. Data were collected during a design engineering project at a top 100 internationally ranked university. The project team consisted of ten team members; all were enrolled in the same masters level track. The project was conducted between March and December 2012 (with summer break through June, July and August). Project work was scheduled for Mondays and Thursdays, consuming 50 per cent of the student's school time. A Stage-Gate project model was used to plan the project. The aim of the project was to develop an innovative modular tiltable bracket for a large international telecom equipment supplier.

In order to track patterns, the idea was to quantify and thereby measure participants' perceptions, which were then matched up with the factual events that had taken place. Given that two authors of the paper were responsible for tracking inside information through observations, keeping track of project documentation and entering a daily update on their activity log, the qualitative nature and depth to the figures collected became more relevant to act on. The activity log consisted of tasks and activities that were conducted each project day. The survey was implemented and initially guided by the coach. However, the routine work of data collection and implementing a procedure that would make everyone contribute on a similar level was conducted by the co-authors.

This setup provided a two-sided – internal and external – version of activities that were performed and the effects they had on the overall work. In addition to the two-sided, unstructured observations made, participants completed written feedback assignments that pinpointed some of the activities that were performed.

Each team member filled out a survey that asked how they thought the work was progressing for the team (e. g., perceived team productivity). A seven-point Likert scale was applied: every member wrote down a value between 1 and 7, where 7 meant extremely productive and 1 meant poor productivity, with hardly anything completed.

In addition, the survey also asked about the team's perception of percentage completion towards the next gate. Every team member rated how much work for the next gate had been completed. The completion value was rated in a perceived percentage, between 0 and 100 %.

Finally, each team member distributed their work activities in four categories: non-IT related, IT work with documentation, IT work without documentation and engineering and calculations (with IT). 100 % of the tasks were distributed between the four categories in order to see what each team member had been working on during the day. Examples of work in each category were included to aid the students in distributing their work activities.

The surveys were collected, all data entered into spreadsheets and then visualised in the form of tables and graphs. Patterns could therefore easily be spotted. The tables and graphs acted as discussion topics during the morning meetings. The test data were further analysed in the spreadsheet software, as well as using MATLAB to calculate statistical data, such as mean values, standard deviation and maximum and minimum values.

The poll data were plotted, showing highs and lows in perceived productivity. The first step towards mathematically defining highs and lows was to forecast a minimum value for each data point using the Weighted Moving Average method. The minimum value was chosen, since it showed the most significant change from the previous session, resulting in a high or a low. Data for the previous three occasions, with the most weight given to the most recent data point, were used to forecast the value using equation 1 below.

$$P_n = \frac{3 \cdot A_{n-1} + 2 \cdot A_{n-2} + 1 \cdot A_{n-3}}{6} \tag{1}$$

Where P_n is the forecast value for data point n and A_n is the actual value. The error ε_n between the forecast value P_n and the actual value A_n was then calculated for each data point n with equation 2 below.

$$\varepsilon_n = A_n - P_n \tag{2}$$

The highs and lows were then identified using the following conditions expressed in equation 3 and 4.

$$\text{Low: } \varepsilon_n \leq -\text{Mean standard deviation AND } A_n < 4 \tag{3}$$

$$\text{Peak: } \varepsilon_n \geq \text{Mean standard deviation AND } A_n \geq 4 \tag{4}$$

Finally, measures of productivity and work activity distribution were compared to see if any patterns could be spotted between these measurements. For each survey answer that corresponded to the current occasion's highest and lowest productivity value, their work activity distribution values were saved in a separate spreadsheet. When this was done for all data points, the mean value for work activity distribution was calculated separately for the highest and lowest to see if a certain work activity could be associated with high or low productivity.

4 RESULTS

Measurements were taken on 33 occasions (280 individual answers for P and C, 115 individual answers for work activity distribution) out of the total number of 37 occasions. For an outline of the main project activities starting from week 16 to week 48, see Table 1. The gates represent decision points in the stage-gate model used in the project (Maylor, 2010).

4.1 Perceived productivity

This data were collected during 33 workdays. The maximum, minimum and mean values for perceived productivity are illustrated below (figure 1), where peaks and lows are identified and highlighted. Three peaks were identified (yellow circles), labelled P1 to P3, and four lows were identified (red circles), labelled L1 to L4.

Table 1. Main project activities

Week	Main activities
14-15	No measurements or activity log for these weeks (2 + 2 occasions)
16	Site visit, manufacturing and market research Gate and board meeting
17	Documenting site visit, ideation sessions
18	Ideation session, usability test
19	Document ideation sessions and usability test. Preparing for concept screening
20	Idea screening (used methods include Spider web diagram and Pugh's matrix)
21	Preparing and attending board meeting Gate and board meeting
22-35	Summer break
36	Concept improvements and preparing new board meeting
37	Board meeting and further improvement on the three remaining concepts Board meeting
38	Creating CAD models, prototyping
39	Preparing and conducting usability session with technicians
40	Documentation of a usability session
41	Preparing and attending board meeting Gate and board meeting
43	Starting to write the report and producing final prototyping documents and files
44	Report writing, sending in prototype documents and starting FEM analysis
45	Report writing, FEM analysis and concept refinements, including CAD modifications and some calculations regarding locking mechanism
46	Final refinements of concepts (CAD and FEM) and report writing
47	Summarising the report, postponing the deadline and preparing the final presentation Gate
48	Preparing and executing the final presentation Final presentation

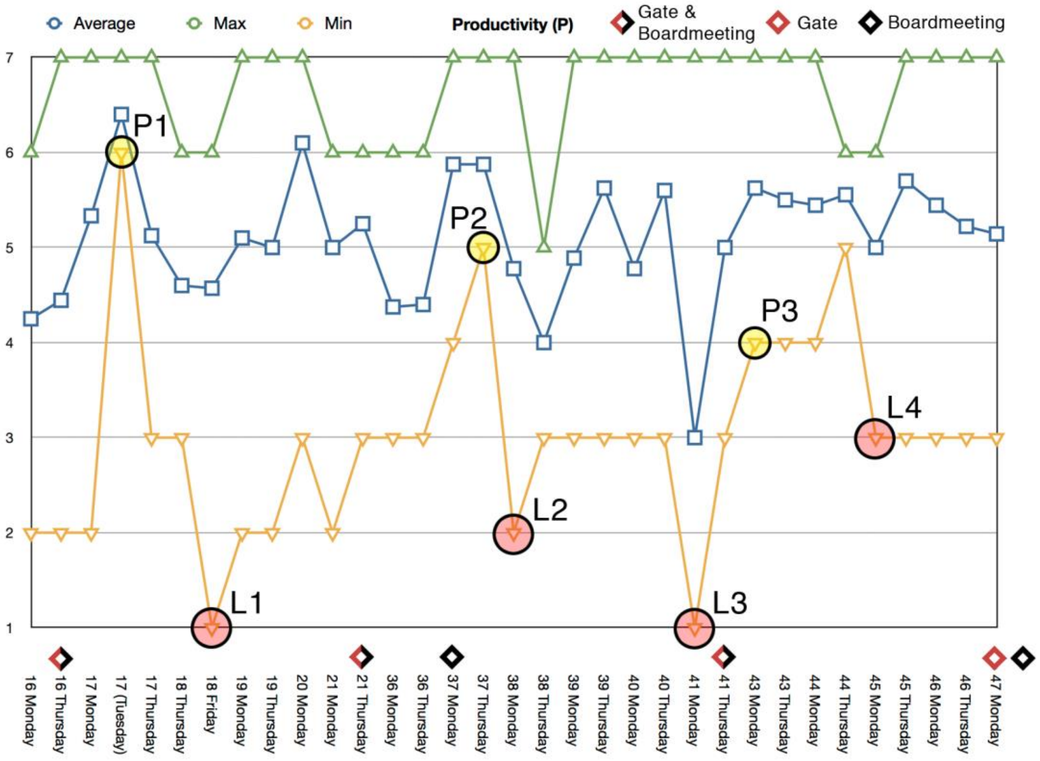

Figure 1. Peaks and lows are highlighted in yellow and red, respectively

Table 2 below explains the activities that occurred on peak and low dates.

Table 2. Peaks and lows with a description of activities.

Peak/Low	**Activities**
P1	The entire team gathered for an extra two-hour ideation session.
P2	New information was received from the project owners. They gave the team feedback on all concepts by stating how they all could be improved.
P3	This workday occurred after an examination period and a board meeting. The final report was starting to be created (structure and layout) and the CAD files for the final prototype were developed.
L1	Another extra ideation session focused solely on a subsystem of the product, the mounting solution, and was considered as an extra session in relation to the other ideation sessions.
L2	This day was the day after a board meeting, where a final decision was made regarding which concepts should be further developed. On this day two new project leaders were selected by the group.
L3	The workday before a board meeting. Presentation material was prepared and documentation updated.
L4	The team continued working with the final report and writing tasks were delegated.

4.2 Completion

This data were collected during 33 workdays. The maximum, minimum and mean values of the perception of stage completion are illustrated in figure 2 below.

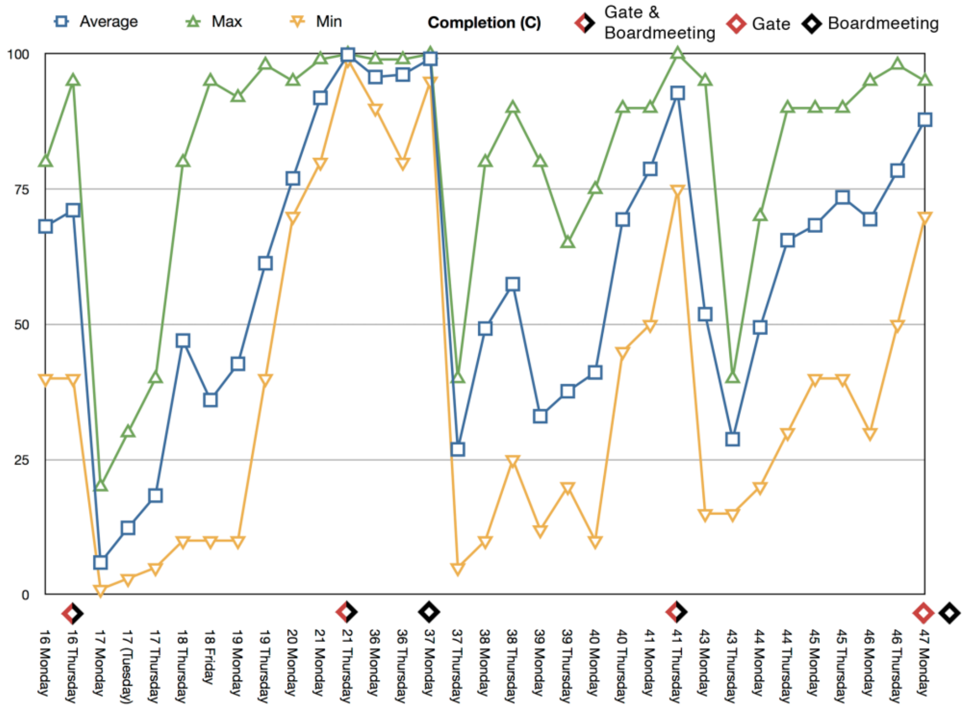

Figure 2. Perception of stage completion plotted throughout the project

From week 16 to week 37, the second stage of the project (ideation stage) occupied the entire team in developing concepts. In the autumn (weeks 36 to 47), one gate was removed and two new project leaders were introduced. We can clearly see that there was some confusion regarding when a stage ended and the next stage began.

4.3 Work activity distribution

Figure 3 below illustrates the average values of all collected data during the time when all three measurements were being taken in student design engineering project.

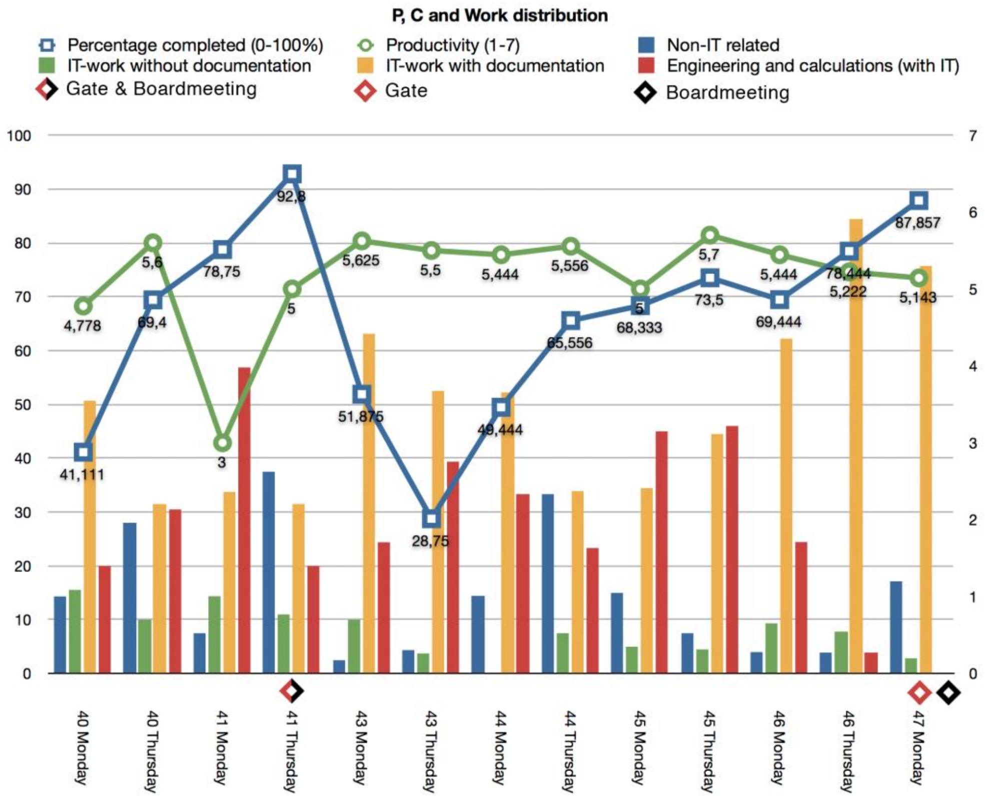

Figure 3. Mean values of last 13 workdays, when all three measurements took place

The work activity distribution data were collected during the last 13 workdays of the project, and the category *IT work with documentation* was scored highest on almost every workday due to the writing of the final report. The second-highest-rated category was *engineering and calculation*, followed by *IT work without documentation* (i.e., various forms of meetings); finally, *non IT related tasks* was the lowest rated category throughout the final 13 days of the project.

Patterns between productivity and work activity distribution were analysed, but no major patterns were identified. The result from the analysis of connections between productivity and work activity distribution is presented in table 3.

Table 3. Analysis of patterns between productivity and work activity distribution

Productivity	Non-IT work	IT work with documentation	IT work without documentation	Engineering and calculations (with IT)
Highest	12.6 %	31.4%	12.6%	39.9%
Lowest	20.5%	46.3%	4.2%	27.1%

5 ANALYSIS

The aim of this paper was to detect patterns in self-evaluation of perceived productivity and provide evidence as to what might cause these patterns. Throughout the project under investigation, self-evaluation of perceived productivity was collected continuously after each project day, and long-term patterns were identified. Table 4 lists the peaks and lows and explains why the self-evaluation of perceived productivity rose or sunk on these workdays.

Collecting samples at random occasions could provide the project group with a measure of perceived productivity for an unusual activity and offer immediate response and feedback. Therefore, continuous measurement of perceived productivity may be more suited for detecting long-term patterns, as well as detecting immediate issues.

The mean value of perceived productivity was lower the workday before a board meeting, and for the workday after the board meeting perceived productivity rose to the same level as two workdays before the meeting. This pattern is shown in Figure 3 by circles L5 and P3. The same indications were spotted in board meetings 1 and 2 (circles P1 and P2). This pattern could be explained by the task of preparing a presentation using PowerPoint. All ten team members could not be a part of this important deliverable, and the progress of the project slowed down.

Table 4. Implications of peaks and lows

Peak/Low	Implication of the activities
P1	The session was planned in advance, and the outcome of the session was that many new ideas were generated.
P2	After receiving new feedback from the project owners, the team gathered their efforts in improving the concepts before the following board meeting.
P3	After new decisions were made in the board meeting before this workday, the entire team could focus all efforts in starting to work on the final deliverables for the project: the final report and the prototype of the final concept. All team members were motivated and could start to see the end of the project.
L1	This ideation session focused on a sub-part of the construction and had a lower number of participants than the previous ideation sessions. Therefore, this workday was not perceived of as productive compared to other ideation sessions and thus productivity was rated lower.
L2	This low occurred on the workday after a board meeting. The day consisted of meetings where two new project leaders were discussed and voted in. Not a lot of actual project work occurred on this day.
L3	The fourth low occurred on the workday before a board meeting where presentation material was prepared and documentation updated. These activities could not involve all team members, and the workday was therefore perceived as unproductive.
L4	The team continued working with the final report, but some tasks were not completed from the previous workday, and new tasks were more difficult to delegate; this negatively affected perceived productivity.

The peaks P1 and P3 have three main things in common. First, they both kept the entire team occupied because everybody was simultaneously working towards the same goal. Second, all team members could therefore contribute and feel involved in finishing the activity, thus creating a sense of team spirit and accomplishment. Finally, both activities produced documented results that were visible to whole team and a result of a team effort.

Another pattern is visible when looking at the ratings on a long-term basis; when the workday consisted of highly planned activities: i.e. when a document containing an outline of planned activities and the time consumption per activity was developed prior to the workday (shown by peaks P1 and P3 in figure 1). This pattern occurred both when the whole team performed creative exercises in the ideation stage and at the end of the project during writing the final report. Productivity ratings indicated that the team perceived these carefully planned activities as highly productive. This pattern was also shown when looking at work activity distribution for days scheduled for report writing. Contrary to the pattern above, two lows (shown in figure 1 as L1 and L4) occurred on an extra ideation session, as well as on a report-writing day at the end of the project.

It would be interesting to be able to produce a productivity/effectiveness rating for the entire project, as has been done in previous studies (Brewer & Mendelson, 2003), and then use the rating as a basis for deciding whether the project should be cancelled or continued. The productivity rating also indicated the major problem of engaging all team members in producing productive work. On almost every workday, at least one team member scored a low productivity rating. On a team of ten members, it is clearly difficult to involve all team members and distribute work amongst them to achieve a highly productive workday. Another phenomenon occurred in the autumn due to changes to the Stage-Gate planning. External factors affected the perceived productivity, when board meetings planned for the end of every stage were rescheduled. Productivity sunk the same way before gate meetings and then rose after. Another implication of external involvement can be seen when looking at the completion ratings. Because of the rescheduling of board meetings (and therefore the stages and gates), team members could not tell when a stage ended and another one started. This pattern was seen in the completion rating, which goes up and down for many workdays when these changes occurred.

External factors also affected work activity distribution, showing an increase in that particular category as new requirements were given. An example of this phenomenon occurred when the team received a new and earlier deadline for the report, resulting in an increase in IT work with documentation. We found no patterns between perceived productivity and perceived stage completion or work activity distribution; this suggests that the additional measurements should be altered or rejected. It would be interesting to analyse productivity in combination with creativity and collaboration, as has been done in past research (Brewer & Mendelson, 2003), and generate an effectiveness rating of the project.

6 DISCUSSION

When a study such as this one is built on self-perceptions, data validity becomes vital in ensuring credibility and transferability. Because the team members rated their perceived productivity themselves and the data were collected by the same people throughout the entire project, personal feelings may have affected their rating. One way of removing personal feelings or other factors that may interfere with the rating of perceived productivity is to collect the data via computer software. Some team members questioned the importance of collecting productivity every day, and they may not have seen the holistic picture of how these data could help the project improving its processes and function more effectively. Observations indicated that a small number of team members were sceptical regarding the measurement of perceived productivity, and this scepticism may have affected their ratings. As the project continued, these feelings of scepticism waned, as team members gained understanding on how the measurements could help improve processes. The measurements also demonstrate how project team members were unsure of what phase they were in and the progress of the project during the first period, following a planned change in project leaders. This is shown in the way completion estimates fluctuate between two gates, as shown in figure 4.

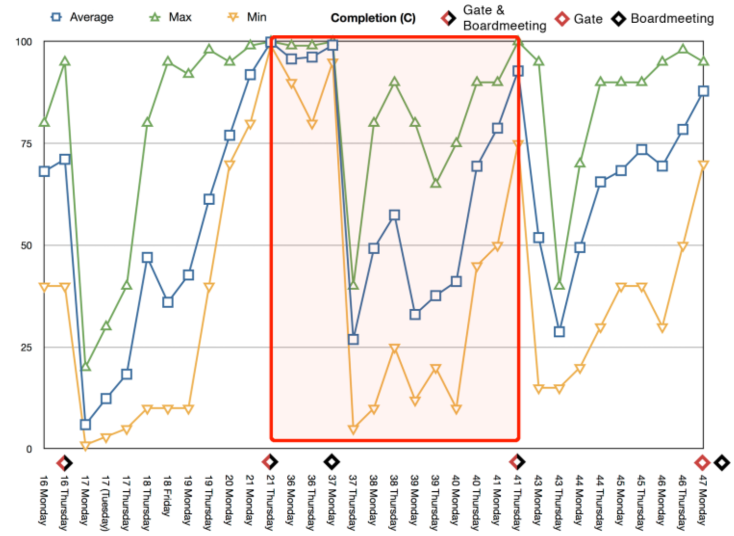

Figure 4. Perceived stage completion: the period of fluctuation is highlighted.

This fluctuation can be explained by both the lack of visual planning and poorly defined activities during the stage: i.e., the activities were too nonspecific and intangible (Maylor, 2010: 301). It would have been better to introduce many smaller deliverables and milestones along the way, instead of only one major deadline (in this case the stage deadline, i.e. the gate).

Another aspect to consider is how this system would function and be accepted in a corporate environment. Because this paper studies design engineering projects in an educational environment, many personal factors – such as different educational backgrounds and age differences in teams, along with altered environmental factors – differ from those found in projects carried out in companies. The different perspectives on the perceived grading underscore uncertainties connected to the individually traced productivity measurements. Other aspects, such as organisational structure and proximity levels of team members, could contribute to fluctuation in productivity.

The study provides insights in how to better enable process improvement. Confirming the suggestions from past studies (Bashir & Thomson, 1999), the implementation of graphic metrics creates a necessary guiding step towards process improvement and project refinement.

7 CONCLUSIONS

Tracing patterns to derive indications for project management and to allow team members to better allocate their resources and concentrate their efforts allows a graphical matrix to evolve over time. Based on individual scores, this matrix pinpoints project activities and their effects on team efforts and efficiency. This study indicates that independent of the nature of an activity (i.e. what is being made at a certain time and place), planning and execution of efforts are what determine the overall efficiency of student engineering design projects in terms of individuals' perceived performance. Consequently, a highly planned activity that occupies the entire team and has visible and documented result is perceived as productive, regardless of what the nature of the activity. Peak values and low values provided an in-depth log of critical incidence showing what took place and what influences the activities in question had on the project team. In this case, peaks and lows indicated action points to be scrutinised not only by project members and project management but also by coaches and course administrators in terms of their implications for facilitation of course design in the future. Further research may consider alternative metrics for perceived productivity in order to highlight other important factors linked to productivity. Team compositions and team sizes should also be areas worth attention in future studies, both for industry projects and for academic engineering design projects. Additionally, further testing of the metrics is suggestively made in other projects and type of settings to validate or propose alternatives to the authors' findings and arguments.

REFERENCES

Bashir, H. A. and Thomson, V. (1999) Metrics for design projects: a review, *Design Studies*, **20**(3), pp. 263-277.

Blumenfeld, P. C., Soloway, E., Marx, R. W., Krajcik, J. S., Guzdial, M. and Palincsar, A. (1991) Motivating Project-Based Learning: Sustaining the Doing, Supporting the Learning. *Educational Psychologist, 26*(3&4), pp. 369-398

Brewer, W. and Mendelson, M. (2003) Methodology and Metrics for Assessing Team Effectiveness. *International. Journal of Engineering Education*, **19**(6), pp. 777-787.

Carbarry, A. R., Lee, H-S. and Ohland, M W. (2010) Measuring Engineering Design Self-Efficacy. *Journal of Engineering Education*, January 2010, pp. 71-79.

de Graaf, E. & Kolmos, A. (2007) *Management of Change; Implementation of Problem-Based and Project-Based Learning in Engineering,* Sense Publishers.

Karlsson, M., Trygg, L. and Elfström, B-O (2004). Measuring R&D productivity. *Technovation*, **24**, pp. 179-186.

Kim, B. and Oh, H. (2002) An effective R&D performance measurement system. *Omega*, **30**, pp. 19-31.

Maylor, H. (2010) *Project Management*. 4th ed. Rotolito Lombarda, Italy: Pearson Education Limited

Ormrod, J. E. (2006) *Educational psychology: Developing learners*. 5th ed. Upper Saddle River, N.J.: Pearson/Merrill Prentice Hall.

Palmer, J. M and Busseri, M. A. (2000) Improving teamwork: the effect of self-assessment on construction design teams. *Design Studies*, **21**(3), pp. 223-238.

Pappas, R A. and Remer, D S. (1985) Measuring R&D Productivity. *Research Management*, 28(3), pp. 15-22.

Ramírez, Y. W. and Nembhard, D. A. (2004) Measuring knowledge worker productivity: A taxonomy, *Journal of Intellectual Capital*, **5**(4), pp.602 – 628.

Shekar, A. (2007) Active learning and reflection in product development engineering education. *European Journal of Engineering Education*, **32**(2), pp. 125-133.

Xijuan, L., Yinglin, W. and Shouwei, J. (2003) A metrics based task analysis model for design review planning. *Design Studies*. **24**, pp. 375-390.