

AMERICAN UNIVERSITY OF BEIRUT

UNCOVERING THE UNDERLYING PATHOLOGIES IN
CAPACITY PLANNING: MATCHING LOAD TO CAPACITY

by
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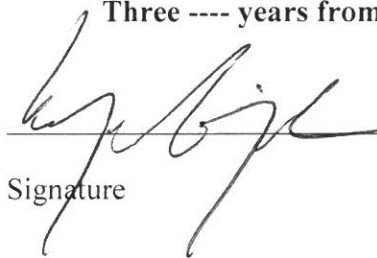
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AN ABSTRACT OF THE THESIS OF

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Title: Uncovering the Underlying Pathologies in Capacity Planning: Matching Load to Capacity

The need for proper and reliable planning is essential for project success. Capacity planning, which is the allocation of activities to available resources, has received good attention in the construction community but few metrics exist to assess its performance. Since it is impossible to improve what cannot be measured, the goal of this thesis is to firstly introduce new capacity planning metrics that will help visualize and understand the current state of capacity planning on construction projects. Is there an overloading or under loading of resources? Secondly, to use these metrics on real data to check whether the metrics paint a proper picture of planning patterns and reliability of planning. The new metrics developed in this research, will attempt to help in assessing the state of equilibrium in choosing the weekly load of tasks to match the existing capacity, or at least, to minimize the gap between the two as much as possible. These new metrics, in theory, will achieve the goal of informing planners and last planners about the status of load vs. capacity, the matching between the two, and the reliability of capacity planning on a project.

Furthermore, the metrics were applied to real data from two on-going projects in the US. The two projects were analyzed individually, and then compared. The metrics showed the performance level each project and proved that (1) there is a mismatch problem between load and capacity, (2) teams on projects are not carrying out proper capacity planning techniques, (3) one cannot look at performance metrics such as the Percent Planned Complete (PPC) alone to assess the performance of projects and the allocation of resources, (4) one cannot look at a single metric to analyze performance and reliability since no metric is a standalone metric, (5) a time-series analysis showed that most teams do not learn from previous mistakes, and make decisions independent of previous ones, (6) some teams focus on one aspect of performance such as allocation of resources or matching load to capacity and neglect the other aspects, and (7) although teams are knowledgeable of the critical activities on the WWP, they do not execute them because of either improper priority ruling or randomly assigning the resources to activities on the WWP regardless of whether the activity is critical or non-critical.

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CHAPTER I

INTRODUCTION

A. Motivation

Planning is an essential step in managing production flow on a project. If the proper time and resources are adequately allocated to planning efforts, the probability of success of the project will increase. Furthermore, much of the risk, that may not have been perceived prior to planning, can be greatly reduced (Aziz and Hafez, 2013). The investment in defining and developing the scope of the project, the requirements, and technical specifications have a positive impact on the success of a project (Dvir, Raz and Shenhar, 2003). But although planning is very crucial at early project stages, ongoing planning during production which includes capacity planning is instrumental in shaping production; and thus, worth studying.

B. Problem Statement

A lot of research has gone into understanding the planning and the scheduling of tasks from a chronological point of view, but there is also the planning of how to assign the activities and tasks (the load) to the available labour, equipment, and resources (the available capacity). This is known as capacity planning. With this new face of planning comes another dimension to the problem of planning and scheduling, which is the issue of matching load to capacity. How much of the activities should we allocate to the labour? How much work can the labour force accommodate at a time? Is there an optimum ratio between load and capacity? It is important to study the balance problem between load and capacity. Allocating adequate time and resources to planning is only one solution to the problem, but it cannot contribute to the success of the project if there is a mismatching problem between capacity and load.

The main research goal that this thesis will attempt to address is the following.

Can we prove the existence of a mismatch problem between capacity and load? Are there adequate metrics to assess the status of resource allocation? If not, can we develop reliable ones? Can the new metrics explore problems in capacity planning?

C. Significance of Study

In some instances, construction companies are overloading their resources and sometimes the resources are not being efficiently employed. Thus, an imbalance between load and capacity arises (Gonzalez et al., 2010), and this in turn can lead to waste in terms of time, money, resources... (Shehata and El Gohary, 2011). By developing new metrics and using them on a construction project, planners can track their performance, identify their problems, and work on fixing the issues that arise. Therefore, this study will help in showing last planners the anomalies in capacity and resource allocation and in matching capacity to the required load.

CHAPTER II

LITERATURE REVIEW

A. Project Planning

The level of planning exerted on a construction project highly affects the extent of the project's success. The upper third of projects, when it comes to completeness of planning, had an 82% chance of meeting their budget goals (Hamilton and Gibson, 1996). This leads to the question of how much planning is enough planning?

Research suggests that not enough time is allocated to properly plan for the average project. Furthermore, the effort put into the planning phase has been found to have the strongest relationship with the overall project success. When the level of effort during the planning phase is reduced, final value to customers, stakeholders, and the company is often reduced. On the other hand, projects with planning phases that are too long had low success ratings, similar to the projects with short planning durations low and planning efforts (Serrador and Turner, 2015).

B. Task Planning

Different stages of the project require different levels of planning effort and control. Planning is performed from a long-term perspective first, and from a short-term perspective later on. The long-term planning phase is where the major project milestones are set, after which the milestones are broken down into phases. Later, short-term planning starts, where 6-week look-ahead plans are set, that are then broken down to weekly work plans. Therefore, planning is performed in greater detail the closer we get to start the activity (Hamzeh and Langerud, 2011).

Similarly, a task that is planned in this way will have fulfilled the objectives and requirements it sought out to fulfil when it is executed and completed.

Planning involves several aspects including cost, scheduling, quality, and making sure that the prerequisites of the task are well-defined and available (Hamzeh, Zankoul and Rouhana, 2015). Additionally, an important step in task planning is the analysis of the potential problems that might arise (a what-if analysis) (Junnonen and Seppanen, 2004). After all, the emergence of problems is largely due to the existence of unforeseen circumstances and the presence of variability.

Furthermore, due to the dynamic and uncertain nature of construction projects, there are always "new" tasks that emerge during the week which they are to be executed. These are the tasks that are "not included in the weekly schedule or are included in it but are allocated within the wrong time frame." (Rouhana and Hamzeh, 2016). Thus, these "new tasks", are activities that were not part of the initial plan and task breakdown but have now appeared as activities that need to be executed for the completion of the project.

C. Variability

Variability is a fact of life that. It is ubiquitous, and the field of construction is no exception. Ben-Haim and Laufer (1998) distinguished between two types of uncertainty. It can either be structured, which is the usual year to year variation of the weather, or unstructured which is "a substantial information-gap between what we do know and what we need to know to perform optimally" (Ben-Haim and Laufer, 1998). Furthermore, variability negatively affects the many aspects of project performance and "leads to ineffective production, increased cycle times, increased cost, and derailed plans" (Gupta, Gonzalez and Miller, 2012).

When it comes to construction projects, variability can be detected in factors such as the production rate, the productivity of labour, and the schedules of construction (Gonzalez, Alacron and Molenaar, 2009). Variability have been acknowledged as reasons for poor construction project performance (Ballard and Howell, 1998). Moreover, the Parade Game was created to illustrate how variability impacts performance and production. It can be concluded that variability and unreliable work flow cause a decrease in throughput, a delayed completion date for the project, and an increase in waste (where some production phases do not use their full output capacity because “they starve for resources”) (Tommelein, Riley and Howell, 1998).

D. Buffers

Lindhard and Wandahl suggest two methods to reduce/accommodate variability. The first method is to increase flexibility by adding float to critical activities, which helps accommodate variability in productivity and improves the ability to react to unforeseen happenings. The second approach suggested is to use buffers to attain flexibility. “The workable backlog should be supplemented with flexible buffer activities. Flexible buffer activities are activities that are not tied to the schedule” (Lindhard and Wandahl, 2012).

Buffering is a well-known go-to practice in project planning. Buffers, whether inventory buffers, capacity buffers, or time buffers, are seen as a tool to absorb and/or reduce the effects of problems and issues by way of accommodating uncertainty and variability (Sakamoto et al. 2002). But how much buffering is enough?

According to Gupta et al. (2012) the problem between productivity and the size of the buffer seems to be a “balance problem”. The smaller the buffer size, the lower the productivity,

and the higher is the sensitivity of production towards variability. There is a certain buffer size beyond which an increase in the buffer size will have “no significant advantage in mitigating productivity loss due to variability”. Thus, even if buffers may not significantly improve productivity, they do provide protection to productivity levels against variability (Gupta, Gonzalez and Miller, 2012). Furthermore, an adequately “pooled, resized, relocated, and re-characterized buffer” can aid in shortening project duration short of radically increasing costs (Park and Pena-Mora, 2004). In addition, by applying a reliability and stability buffering approach, “(1) the amount of hidden errors and latent changes was reduced; (2) the flexibly located and distributed buffers helped identify the predecessors’ errors and changes in concurrent design and construction; (3) the impacts of hidden errors and changes were minimized, preventing their ripple effect on the succeeding activities; and (4) the quality of the coordination process was increased” (Lee et al. 2006).

E. Limited Resource Allocation

Ideally, construction projects would like to have ample resources to never be obligated to prioritize the tasks to allocate the available resources adequately. Resource variations are “impractical, inefficient, and costly” when they occur during construction (El-Rayes and Jun, 2009, Koulinas and Anagnostopoulos, 2013). In reality, resources are rarely sufficient, and more often than not, are limited and sparse. Therefore, planners end up having to allocate their resources using a priority rule, which per Khattab and Soyland (1996) performs better than a CPM-based rule. CPM is built on the postulation that the availability of an unlimited amount of resources for execution of the tasks exists and is therefore considered when a project is task-constrained or activity-critical (Kastor and Sirakoulis, 2009). Furthermore, limited resource

allocation is used when the project is resource-constrained or resource-critical and thus, since the project would already be running late, the goal would be to keep the exceeded project duration to a minimum (Khattab and Soyland, 1996).

Damci, Arditi and Polat (2013) suggested that an increase in efficiency of the sequence of the project is a crucial aspect to achieve project goals and aids in the solution to the resource leveling problem. Ponz-Tienda et al. (2017) proposed an algorithm to deal with the problem with several resources aiming to abate variations. Some objective functions were studied by Damci and Polat (2014) to better understand and measure project sequence efficiency, but no metrics were suggested to show that there are in fact fluctuations and mismatching issues between these shifting resource levels and tasks to be executed.

F. Matching Load to Capacity

So far, the dynamics of variability have not been completely understood. Therefore, planners often fall into the problem of matching load to capacity which is not an easy task to achieve. Ballard (2000) defines load as the quantity of work needed to be done in a specific time allotted by planners, and capacity is the quantity of work a crew can complete given their tools, methods of work, and conditions on-site. When load and capacity estimates diverge, the planning crew must either alter load to match capacity by postponing or fast-tracking work flow, alter capacity to meet load by changing the quantity of resources, or an amalgamation of both (Gonzalez et al., 2010).

Production planning endeavours to match load to capacity with top accuracy based on given circumstances (Ballard et al., 2007). Thus, production planners require information

regarding workloads and resource capacity (Kim and Kim, 2012). Kim et al. (2008) came up with a workforce information (level of skill, history of accidents, etc.) database to help solve the problem of matching load to capacity. “The workforce database system allows the user to consider workforce capacity in production planning” (Kim et al. 2008).

Despite the plethora of research on the importance of matching load (tasks put on the weekly work plan) to capacity (available resources), no clear metrics were derived to assess capacity planning in conjunction with the Last Planner System (LPS). This study proposes seven primary metrics and four secondary metrics to assess the performance of capacity planning to guide the last planners in managing and controlling production and workflow.

CHAPTER III

RESEARCH OBJECTIVES & METHODOLOGY

A. Objective 1: Develop metrics to better visualize the state of capacity planning

Planners cannot manage what they cannot measure. Furthermore, measurement cannot happen without having proper metrics. In some instances, construction companies are overloading their resources and sometimes the resources are not being efficiently employed. Thus, the need for metrics, to help us better visualize how we are loading our resources, arises. Furthermore, we realize that there are not enough metrics in the field of planning that aid in adequately describing the state of capacity planning on a certain project. Accordingly, in an effort to better understand and attempt to find a proper solution to the problem of matching load to capacity, we devised seven primary metrics and four secondary metrics that will serve as being somewhat descriptive of the state of planning on a project in general, and capacity planning in particular. These metrics are presented in chapter V.

B. Objective 2: Apply the metrics to understand the load-capacity mismatch problem

After developing the metrics, they were applied to real data gathered from two projects in the USA which had sufficient information for the study carried out. The data, which has been acquired from an outside source, was pre-processed in order to make correlations and to understand the relationship between these metrics. By applying these metrics to the data, this study was able to prove their reliability and to highlight the issues in capacity planning.

C. Methodology

A certain process was carried out throughout the lifetime of this research. Initially, a survey of the literature was conducted, and metrics that are not in the literature were created. Next, data was acquired from an outside source and was pre-processed. Then, the information required to calculate the parameters for the metrics was extracted from the pre-processed data. After finalizing that step, the metrics were calculated, and graphs were generated. These results were analysed and conclusions were made. This process is summarized in figure 1.

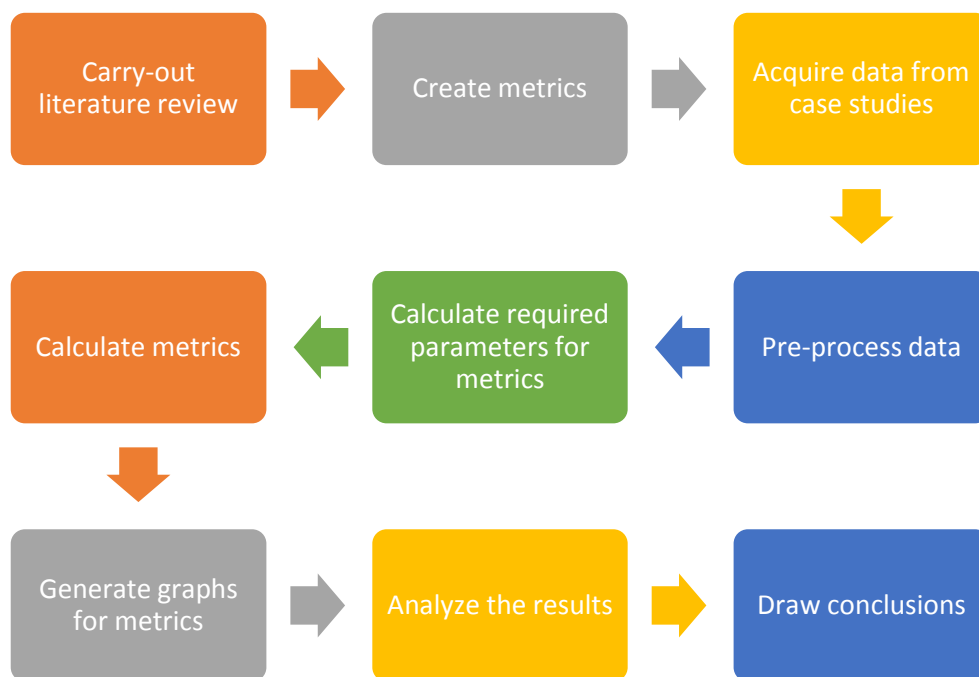


Figure 1 - Process Flowchart

A survey of the nature of this study and the research of objectives presented, suggests that a case-study based research approach is the most fitting. Case-study research: (1) is a suitable approach for answering questions relating to ‘how’ and ‘why’, when no control for behaviour is essential, and when research emphasizes on contemporary matters; (2) employs both quantitative and qualitative approaches to describe phenomena; (3) can use quantitative means to find answers to questions; (4) can explain underlying ties using actual evidence and utilize

observation to prove or disprove causality by exposing any false correlations; (5) uses numerous sources of proof in a natural setting that includes temporal and contextual facets of the variables under study; (6) exposes the dynamics of occurrences explaining the phenomenon being studied; (7) can employ uncompromising data collection, description, and triangulation; and (8) offers qualitative understanding when deriving inferences and analysing results (Meredith 1998, Stuart et al. 2002, Yin 2003).

In order to achieve the research objectives previously mentioned, the following tasks were completed.

1. Task 1: Develop the metrics

Before coming up with the metrics introduced in this thesis, this study distinguishes between three types of activity clusters as shown in figure 2. Within each cluster, there are two colours, red and green. The green pebbles represent normal activities while the red pebbles represent critical/required activities.

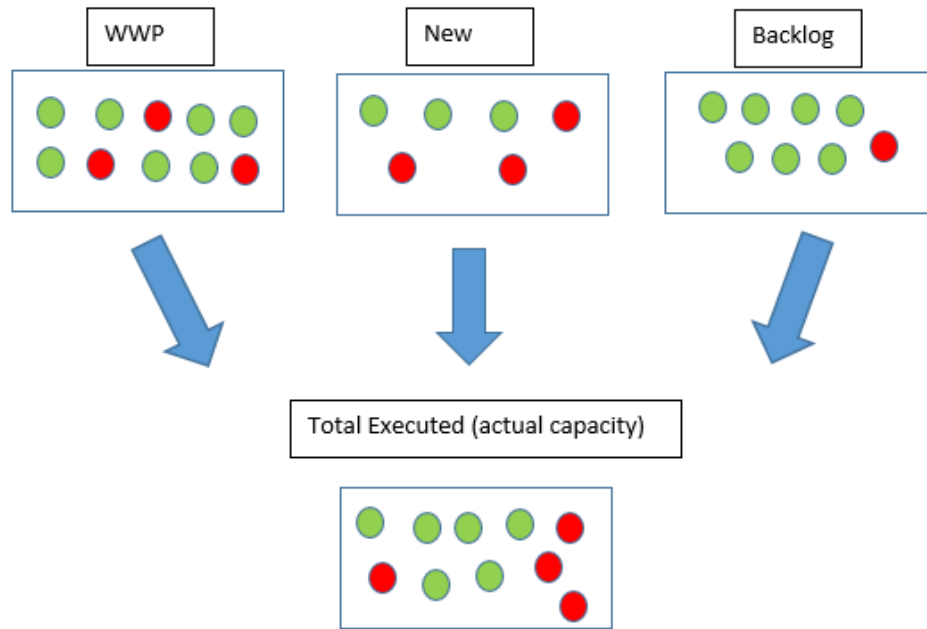


Figure 2 - Activity Clusters

The first cluster, as depicted in figure 2, is the WWP cluster, where WWP stands for Weekly Work Plan. This group of activities consists of all the tasks that have been committed to be completed that week. The second cluster of activities is called New which are tasks that need to be executed during the week as pre-requisites or co-requisites to other tasks. Notice also that some tasks are required, in other words critical, (red) while others are not (green). The third cluster, Backlog, is representative of the activities that make up the backlog. These are the activities that are assigned when the team has completed the activities that they have committed to complete and they have extra resources to work more or are stuck on an issue and instead of having idle resources, they execute activities from the backlog.

Furthermore, figure 2 shows a fourth cluster of activities, Total Executed, which is the actual activities that have been executed that week (i.e. the actual capacity). The three clusters mentioned above contribute to the Total Executed cluster of activities as depicted in figure 3.

The tasks that have been executed in that week constitute the actual capacity and the tasks that have been chosen to be on the WWP are the chosen load.

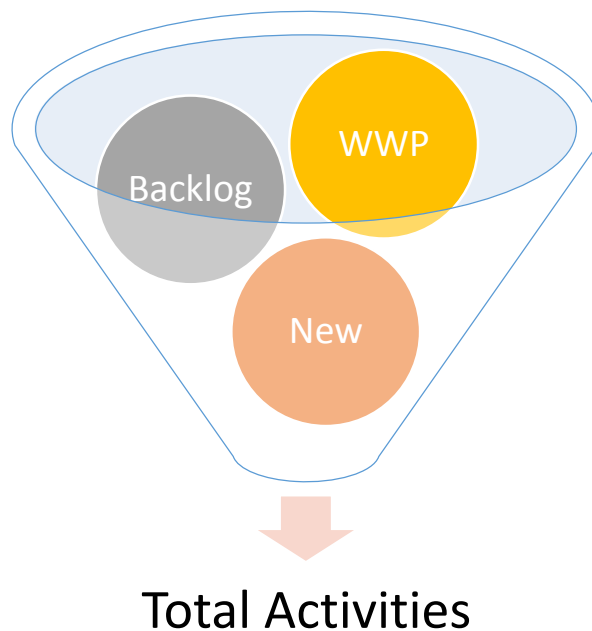


Figure 3 - Contributions to Total Activities

2. Task 2: Acquire and pre-process the data

The data used to validate the metrics presented in this study, was acquired from an outside source. It was collected from two construction projects in the United States of America. The question of why these projects were chosen begs an answer. The projects that were required to carry out this study had to have a substantial database of information. The teams on the project track milestones, adjust the schedule, and apply advanced LPS assisted by a planning and scheduling software called vPlanner, which is targeted for production planning and Last Planner System. vPlanner solves two vital matters when applying the Last Planner System that call for substantial effort from the project teams. “The first is the alignment between near-term and long-term project plans and the second is the constant management of the near-term plans to identify

and remove constraints that may impact workflow reliability.” (vPlanner, 2017). Furthermore, Hamzeh et al. (2012) showed there is a gap between the master schedule and WWP. In other words, the activities that are placed on the WWP cannot be distinguished as being either critical or non-critical activities. However, on this project there is no gap, which means that tasks on the WWP are known whether they are critical. Thus, these are some of the reasons why these two projects were deemed compatible for this study.

The data includes details on multiple tasks and activities required to execute the project. Each task has multiple parameters including but not limited to, task ID, weekly workplan ID, team ID, task status, date created, workplan start date, etc...

Note that for those who do not use vPlanner or do not have access to the software, refer to Appendix A for the steps to follow to gather the required data and calculate the metrics created in this study.

The first step in pre-processing the data was splitting the projects into two separate files. Next, looking at each project separately, it was noticed that there are multiple teams working on a project, and each team had its own weekly workplan start date, and therefore its own weekly workplan. Project 1 had 9 teams, and project 2 had 4. Each team, which is made up groups of different trades, represents a part or subset of the project. These teams meet on a weekly basis, they even sometimes meet more than once a week if need be, thus the WWP had to be averaged in some cases (a WWP is between 6 to 8 days on average). Furthermore, different teams meet on different days, which leads to different WWP start days (i.e. the WWP of one team might start on a Monday, whereas the WWP of another team might start on a Thursday). The tasks pertaining to each team were separated into different worksheets. This was done by grouping all tasks that

have the same team ID together on one worksheet. Note that two teams from project 1 and one team from project 2 were excluded since they were considered to have a short life as compared to the other teams. The aforementioned teams were most probably created for a certain purpose and for a short period and were later on dissolved.

Note that the methodology detailed and explained in this chapter was the same methodology followed to pre-process and extract the required information from the data of both projects.

To be able to calculate the metrics that are introduced in the following chapter, the activity clusters mentioned in the previous section need to be identified and calculated for each week. Thus, the weekly workplans for every week (for each team) were identified and the number tasks per week was calculated. Note that all tasks with the same weekly workplan ID are tasks that belong to the same weekly workplan. Furthermore, each task has a status description as detailed in Table 1.

Table 1 - Task Status Description

Status	Description
Committed	A task that has been committed to the weekly workplan (WWP).
Committed Pending	A task that has been tentatively committed to the WWP.
Committed Unplanned Constraint	A task that is New but has been added to the WWP.
Completed	A task that has been executed.
Completed Backlog	A task that was on the Backlog and has been executed.
Completed Unplanned Constraint	A task that is New and has been executed.
On Going	A task that has started, but has not yet been complete (may or may not be on time).

After dividing the teams up and gathering the tasks of each team as per their status description and placing them in tables like the table shown in figure 4, the total number of weeks was derived as well as the total number of activities per week. The total number of activities per week was calculated by summing columns C through H (refer to figures 4 and 5).

A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Z	AA	
		Status of Activity						Activity Clusters						PPC			Critical		Metrics					Waste		Starvation
Week	WWP Start Date	Committed Pending	Committed Unplanned Constraint	Completed	Completed Backlog	Unplanned Constraint	On Going	On Going (Late)	Total Activities Cluster	New Activities Cluster	Completed Backlog Cluster	WWP Cluster	Completed Activities Cluster	Completed New	Completed from WWP	PPC	Critical Activities	Completed Critical Activities	CLR	RCR	RPC	WD	WDR	1-RCR	1-RPC	

Figure 4 - Sample Table

A	B	C	D	E	F	G	H	I	J	
		Status of Activity								
Week	WWP Start Date	Committed Pending	Committed Unplanned Constraint	Completed	Completed Backlog	Completed Unplanned Constraint	On Going	On Going (Late)	Total Activities Cluster	

Figure 5 – Partial Sample Table: Status of Activity

Next, the New activities were extracted using an If Statement. The condition was that if the activity had a “Date Created” that was within the weekly workplan for a certain week (i.e. if the date created > weekly workplan start date), then that activity is considered as being a New activity and is depicted with a 1, otherwise it is not a New activity and is depicted by a 0. The New activities are summed per week and entered into column K (New Activities Cluster) shown in figures 4 and 6.

A	B	C	D	E	F	G	H	I	J	K	L	M	N
Status of Activity									Activity Clusters				
Week	WWP Start Date	Committed Pending	Committed Unplanned Constraint	Completed	Completed Backlog	Completed Unplanned Constraint	On Going	On Going (Late)	Total Activities Cluster	New Activities Cluster	Completed Backlog Cluster	WWP Cluster	Completed Activities Cluster

Figure 6 – Partial Sample Table: Activity Clusters

The subsequent cluster of activities that was extracted was the Completed Backlog Cluster. As mentioned previously, the data available only gives the completed backlog activities and has no information on the total (completed and not completed) backlog list of activities as a whole. Furthermore, it was noticed that some activities that are New have a Completed Backlog status description. But since the New cluster of activities and the Backlog cluster of activities are mutually exclusive sets (refer to figures 2 and 3), one activity cannot exist as both New and Completed Backlog. Therefore, to extract the actual set of Completed Backlog activities, an If Statement was used, with the condition being that if an activity is not new (i.e. 0) and has an end status description as “Completed Backlog”, then it is part of the Actual Completed Backlog set and is depicted by a 1, else it is a New activity and is depicted by a 0. The total Actual Completed Backlog activities are summed each week and added to column L as represented in figures 4 and 6.

The next step in the process is to calculate the task that have been committed to the weekly workplan. Per figure 3, the total activities in a week are made up of the sum of the backlog activities, the new activities, and the WWP activities. But as previously mentioned, there is no information on the total backlog list, only the backlog activities that have been completed. Therefore, the diagram transforms from figure 3 to figure 7 (below). Finally, referring to figures 4 and 6, to get the number of activities on the WWP each week (column M), we subtract the

New Activities (column K) and the Completed Backlog Activities (column L) from the Total Activities (column J).



Figure 7 - Modified Contributions to Total Activities

To finalize the Activity Clusters, all that remains is to calculate the Completed Activities in column N (refer to figure 6). This is calculated by summing all the tasks that have “Completed” in their end status description. But, there are some activities with an end status description of “On Going”, which means that these tasks have started but have not yet been completed. These tasks may or may not be on time. To find out if a task is running late or is on time, there is a column in the raw data called “isLate”. If a task has a 1 in the “isLate” column, then it is running late, but if it has a zero then it is on time. Therefore, an assumption is made that if a task is “On Going” and is on time, then it is considered completed. Otherwise, it is “On Going” but running late, consequently it is not included in the Completed Cluster of Activities. Thus, to calculate the Completed Activities (column N), columns E, F, G, H are summed and column I is subtracted (refer to figure 6).

One final piece of information is required to be able to calculate the metrics, and that is related to the critical activities. How many critical activities are there per week? How many of these have been executed? To answer these questions, we looked at the difference between the committed start date and the last responsible moment start date. Since this study looks at activities on a weekly basis and not on a daily basis, if an activity has a float of less than 5 days, in other

words, if an activity’s float is less than the number of working days in a week, then it is critical. Therefore, if the difference was less than 5 days, then the activity was considered critical (i.e. 1), else it is a non-critical activity (i.e. 0). The weekly number of critical activities was extracted and placed in column R as shown in figure 8.

J	K	L	M	N	O	P	Q	R	S
Activity Clusters					PPC			Critical	
Total Activities Cluster	New Activities Cluster	Completed Backlog Cluster	WWP Cluster	Completed Activities Cluster	Completed New	Completed from WWP	PPC	Critical Activities	Completed Critical Activities

Figure 8 - Partial Table: Critical

Finally, to get the number of critical activities that were completed each week, a check need to be made. If the task was critical (i.e. 1) and it had the word “Completed” in its end status description (i.e. “Completed”, “Completed Backlog”, “Completed Unplanned Constraint”), then it was a critical activity that was executed. Furthermore, if it was a critical activity that was “On Going” and running on time, then it would be considered as a critical activity that has been executed. The completed critical activities are summed per week and entered in column S as per figure 8.

As a last step, we need to calculate the Percent Planned Complete (PPC) to measure reliability of planning. According to Ballard (2000), PPC is an indispensable part of the Last Planner System. It is used to measure the effectiveness and reliability of planning by dividing the work performed (i.e. the activities that were committed and have been completed which is column P in figure 8) by the work planned (i.e. the activities that have been committed to the

WWP which is column M in figure 8). The consistent calculation of PPC provides a great way to monitor variability in project planning (Bhaidani et al., 2016).

Consider the following steps taken to calculate PPC every week for each team. To be able to calculate the activities that were committed and completed (column P in figure 8), we have to subtract from the Completed Activities Cluster (column N in figure 8) the Completed Backlog Cluster (column L in figure 8) and the Completed New (column O in figure 8). The Completed New activities are calculated by the following; New activities that have been completed was calculated by using an IF Statement. If the activity is New and has “Completed” in the its end status description, or if the activity is New and On Going (on time), then the activity is Completed New and the sum of these activities per week is placed in column O of figure 8. Now, we can calculate PPC by dividing Completed from WWP (column P) by the WWP Cluster (column M).

3. Task 3: Apply the metrics to the data

Once the data was pre-processed, and the required parameters were calculated, the metrics were applied in an attempt to visualize the mismatch problem between the chosen load and the actual capacity. Chapter V introduces the metrics, presents an explanation for each one, and introduces the parameters required to calculate them.

4. Task 4: Analyze the results

The results from applying the metrics to the data were analyzed, and correlations were made to understand the relationship between the different metrics. The analysis of the results is discussed in a greater detail in Chapter VI.

5. Limitations of the Study

There were some limitations on this study which included a lack of complete information. Data related to the man-hours was required to be able to calculate two of the seven primary metrics, but was not collected and therefore was not provided in the raw dataset. Furthermore, financial data related to the costs was not provided, therefore an earned value analysis was not carried out.

CHAPTER IV

METRICS

Seven new primary metrics and four secondary metrics were created as described below. Note that these metrics are to be used for measurement on a weekly basis when applying the LPS.

A. Capacity to Load Ratio

The first metric is called the Capacity to Load Ratio (CLR). This metric is a comparison of the chosen load with the actual capacity. It is calculated by dividing the total number of activities executed this week by the number of activities on the weekly work plan (WWP), i.e. the activities the team has committed to completing this week. It is a retrospective metric which aids in tracking how close the team is in adequately employing resources. The CLR is calculated using equation (1) below.

$$CLR = \frac{\textit{Total Executed}}{\textit{WWP}} \quad (1)$$

Referring to figures 4 and 9, to calculate the CLR metric per week (column T), the completed activities which make up the capacity (column N) are divided by the WWP cluster which make up the chosen load (column M). Note that if there are no activities on the WWP (i.e. WWP cluster = 0), then CLR will return 0.

J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X
Activity Clusters					PPC			Critical		Metrics				
Total Activities Cluster	New Activities Cluster	Completed Backlog Cluster	WWP Cluster	Completed Activities Cluster	Completed New	Completed from WWP	PPC	Critical Activities	Completed Critical Activities	CLR	RCR	RPC	WD	WDR

Figure 9 - Partial Table: Activity Clusters, PPC, Critical, Metrics

B. Capacity to Load Ratio in Man-hours

The second metric is the CLR man-hrs. It is the same as the CLR described above with one difference; the CLR calculated in equation (1) is at the level of activities while the CLR man-hrs is at the level of the man-hours required to complete the activities. It is calculated by dividing the quantity of man-hours it took to complete the activities that have been executed this week by the quantity of man-hours required to complete the activities committed on the WWP. The CLR man-hrs is calculated using equation (2) below.

$$CLR\ man - hrs = \frac{Actual\ man - hours}{WWP\ man - hours\ Worked} \quad (2)$$

Note that, since the data carried no information on the man-hours, this metric was not calculated and therefore was not used to analyse the project performance.

C. Required Capacity Ratio

The third metric is called the Required Capacity Ratio (RCR) which represents the fraction of completed activities that are required (i.e. activities that are critical). It tells us what fraction of

the completed activities are critical. Referring to figure 10, RCR is represented by the common region in the Venn diagram (shaded purple area) versus the Completed Activities circle (blue).

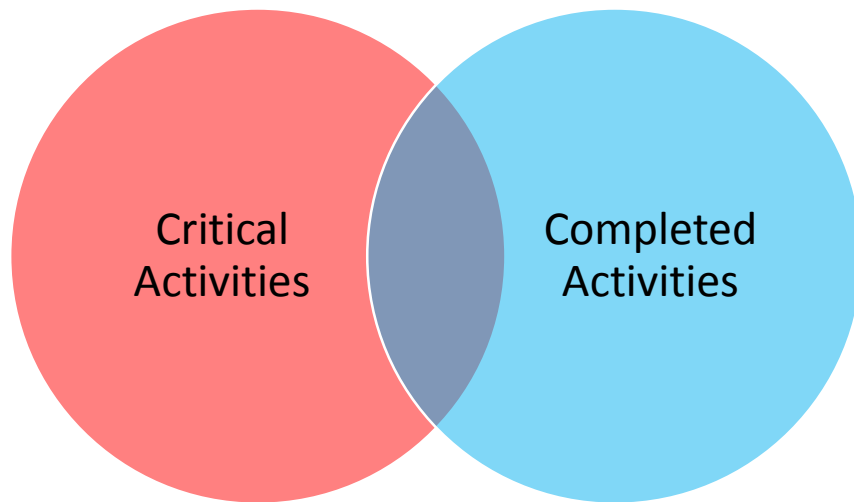


Figure 10 - Critical Activities and Completed Activities

It is calculated by dividing the required activities that were completed by the total number of activities that were executed, as shown in equation (3) below.

$$RCR = \frac{\textit{Required Executed}}{\textit{Total Executed}} \quad (3)$$

Referring to figures 4 and 9, to calculate the RCR metric per week (column U), the completed critical activities in column S are divided by the total completed activities in column N.

D. Required Percent Complete

The fourth metric is called the Required Percent Complete (RPC) which represents the percentage of required tasks that have been completed. Going back to figure 10, RPC is represented by the common region in the Venn diagram (shaded purple area) versus the Critical Activities circle (red). Refer to figure 11 for another illustration of the same idea.



Figure 11 - Total Critical Activities vs. Completed Critical Activities

It is calculated by dividing executed required activities by the total required activities this week, as shown in equation (4) below.

$$RPC = \frac{\textit{Required Executed}}{\textit{Total Required}} \quad (4)$$

Referring to figures 4 and 9, to calculate the RPC metric (column V) for every week, the completed critical activities in column S are divided by the total critical activities in column R.

E. Required Percent Complete in Man-Hours

The fifth metric is the RPC man-hrs which is similar to RPC except that the RPC is at the level of activities, while the RPC man-hrs is at the level of the man-hours required to complete the activities. It is calculated by dividing the quantity of man-hours that were expended to complete required activities by the quantity of man-hours needed for all required activities to be that week to be executed as shown in equation (5) below.

$$RPC \textit{ man - hrs} = \frac{\textit{Required Executed man - hrs}}{\textit{Total Required man - hrs}} \quad (5)$$

As previously mentioned, since the man-hours for the activities on the project were not recorded, metrics that require data on the man-hours to be calculated were not used. The CLR man-hrs and the RPC man-hrs will be used and validated in future research where the man-hours are appropriately and consistently collected.

F. Weekly Deviation and Weekly Deviation Ratio

The sixth and seventh metric are complementary and related. They are both used to assess the deviation from the WWP. The Weekly Deviation (WD) gives us an indication of how far the team has deviated from the WWP, and the direction of the deviation (i.e. if $WD < 0$ then the team is overloading their resources, if $WD > 0$ then then the team is under loading their resources, and if $WD = 0$ then then the team has matched the load to capacity).

The Weekly Deviation Ratio (WDR) is the WD normalized by the WWP for comparison purposes. The WD and the WDR are each calculated by using equations (6) and (7) respectively.

$$WD = Total\ Executed - WWP \quad (6)$$

$$WDR = \frac{Total\ Executed - WWP}{WWP} \quad (7)$$

Referring to figure 4 and 9, to calculate the WD metric (column W) per week, the number of activities on the WWP (column M) is subtracted from the number of total executed activities (column N). Furthermore, to calculate the WDR metric (column X) on a weekly basis, WD in column W is divided by the number of activities on the WWP (column M). Note that if there are no activities committed to the WWP, then WDR will return 0.

Table 2 summarizes all the metrics with their respective equations and descriptions, and Table 3 lists the variables required to calculate these metrics.

Table 2 - New Capacity Planning Metrics (Primary Metrics)

Metric	Formula	Description
Capacity to Load Ratio	$\frac{\text{Total Executed}}{\text{WWP}}$	How many activities that have been committed for the week (all activities on the WWP) vs. How many activities were executed that week.
Capacity to Load Ratio man-hrs	$\frac{\text{Actual man - hours}}{\text{WWP man - hours Worked}}$	How many hours are required to complete the activities on the WWP vs. How many man hours have actually been expended on the activities that have been executed that week.
Required Capacity Ratio	$\frac{\text{Required Executed}}{\text{Total Executed}}$	Out of the total executed tasks for that week, how many were critical.
Required Percent Complete	$\frac{\text{Required Executed}}{\text{Total Required}}$	Out of all the critical tasks for this week, how many have been executed.
Required Percent Complete man-hrs	$\frac{\text{Required Executed man - hrs}}{\text{Total Required man - hrs}}$	How many man hours have been expended on required activities vs. how many hours are required to execute all required activities.
Weekly Deviation	$\text{Total Executed} - \text{WWP}$	How far from the WWP we have deviated and in what direction.
Weekly Deviation Ratio	$\frac{\text{Total Executed} - \text{WWP}}{\text{WWP}}$	A normalized WD for comparison purposes.

Table 3 - Variables included in the calculation of primary metrics

Variables	Description
WWP	Weekly Work Plan, i.e. the activities on the weekly work plan that have been committed to be completed for that week.
WWP man-hours	The quantity of man-hours required to complete all the activities on the weekly work plan for that week.
Actual man-hours Worked	The quantity of man-hours that was actually expended that week to execute the activities that were actually completed.
Required Executed	All the critical activities that were executed that week (i.e. all red circles in Total Executed Cluster).
Required Executed man-hrs	The quantity of man-hours expended to execute the activities that were required.
Total Executed	All the activities that were actually executed that week (i.e. all circles in Total Executed cluster).
Total Required	All the critical activities that are on the WWP, the backlog, and the new critical activities for that week (i.e. all red circles in the 3 clusters).
Total Required man-hrs	The quantity of man-hours needed to execute the required activities that week.

If RCR represents the percentage of completed activities that are critical, then it is safe to say that 1-RCR represents the percentage of non-critical activities that are completed which can be considered as glut (i.e. non-critical activities which are over-indulged with available resources). Moreover, a similar conclusion can be made for RPC. If RPC represents the percentage of critical activities that have been executed, then 1-RPC represents the critical activities that have not been completed. In other words, the activities that are starving for resources. Thus, a Misallocation Factor can be deduced as being the sum between Glut and Starvation. This sum is the waste in capacity planning. Therefore, three secondary metrics to further show the misallocation of resources that takes place on projects were deduced, Waste and Starvation, and are depicted in equations 8, 9, and 10 below.

$$Glut = 1 - RCR \quad (8)$$

$$Starvation = 1 - RPC \quad (9)$$

$$Misallocation\ Factor = Glut + Starvation \quad (10)$$

Furthermore, a fourth secondary metric was created to be able to compare the team deviations between the teams on every project. This metric is called the Normalized Team Deviation (NTD). It is calculated by summing the WDRs over the weeks the team is functional in absolute value, and then dividing the sum by the total number of weeks the team is functional (n). In other words, NTD is the average of the weekly deviations in absolute of a team (i.e. weekly deviation per week). Refer to equation 11 below.

$$NTD = \frac{\sum_1^n |WDR|}{n} \quad (11)$$

Table 4 summarizes the secondary metrics along with their respective equations and descriptions.

Table 4 - New Capacity Planning Metrics (Secondary Metrics)

Metric	Formula	Description
Glut	$1 - RCR$	The percentage of completed activities that are non-critical.
Starvation	$1 - RPC$	The percentage of critical activities that have not been completed.
Misallocation Factor	$Glut + Starvation$	The sum of Glut and Starvation
Normalized Team Deviation	$NTD = \frac{\sum_1^n WDR }{n}$	A normalized team deviation for comparison purposes. Each team has one NTD for the entire project (not a weekly metric but an average metric).

CHAPTER V

RESULTS, ANALYSIS, AND DISCUSSION

A. Results and Analysis of Project 1

1. Team 1 (PIT1)

The first step in analyzing the capacity planning patterns of a team is to look at how the team is loading the available resources. Therefore, we need to look at a graph which shows the committed number of activities (the load) and the executed number of activities (the capacity) for every week. This is depicted in figure 12. Whenever the line representing the WWP activities is above the line representing the Completed activities, then the team is overloading the resources. Similarly, if the WWP activities line is below the Completed activities line, then the team is under-committing (i.e. under loading the available resources). This will be mirrored in the CLR graph in figure 13. Notice that there is a line called the “Matching Line”, which basically represents the ideal situation where the load matches the capacity exactly (i.e. $CLR = 1$). Thus, from equation (1) and the Load vs. capacity graph in figure 12, we can infer that when the CLR line is above the Matching Line (i.e. $CLR > 1$), then the team is underloading the resources. Conversely, if the CLR line is below the Matching Line (i.e. $CLR < 1$), then the team is overloading the available resources. On average, team 1 is overloading the available resources with a CLR of 0.971.

Furthermore, WDR was taken in absolute since any difference, whether positive or negative, between capacity and load is bad and not desirable. A deviation between capacity and load is considered waste because either resources are idle and waiting on work, which means that

the available capacity is greater than the chosen load, or the resources are being overloaded and thus are not capable of executing all the committed tasks, which means that capacity < load. Therefore, graphing the weekly deviation in absolute will just give us an indication of whether there is or isn't a deviation, and the magnitude of said deviation. Overall, team 1 has an NTD, which as previously mentioned is WDR summed in absolute over the number of weeks (i.e. NTD = average WDR in absolute) of 0.131.

As previously mentioned, two secondary metrics (Glut and Starvation) were created to help visualize the misallocation of resources. Figure 14 illustrates the graph of the Glut and the Starvation for Team 1 of Project 1. Since Glut and Starvation are two things we wish to keep to a minimum, the lower the Glut and Starvation the better. If the Glut is high, then the non-critical activities are being executed before the critical activities. Non-critical activities are indulged with available resources (e.g. if Glut = 0.8, then 80% of completed activities are non-critical). Similarly, if the Starvation is high, then there are critical activities that are not being executed. The team is "starving" the critical activities by allocating available resources to non-critical activities before critical ones (e.g. if Starvation = 0.6, then 60% of critical activities are "starving" for resources and have not been executed). Note, that one metric cannot work without the other. Take week 1 as shown in figure 14 as an example. Glut = 0.85 which means that 85% of the executed tasks are non-critical. As a standalone number, this would indicate that the team has severely misallocated the available resources. However, notice that Starvation = 0 (i.e. RPC = 1), which means that 100% of the critical activities for week 1 have been executed. On average, team 1 has 68.3% Glut per week and 40.5% Starvation.

The graph illustrated in figure 15 represents the PPC (Percent Planned Complete). Ideally, PPC, which is a measure of reliable promising, should be at 100% (i.e. all that a team

plans to complete in a week is actually executed by the end of that week.). On average, team 1 has a PPC of 85.7%.

The final graph illustrated in figure 16 is a scatterplot with a trendline which is the result of a time-series analysis of WDR in absolute. The aim of this graph is to see if there is any correlation in the deviation between capacity and load of a team over time. In other words, is the team's decisions affected by past results? Is the team learning from past mistakes? The time-series analysis for team 1 yielded an R^2 of 0.0194, which means that the fitted curve only explains 1.94% of the error. This indicates that the decisions of team 1 are independent of its previous decisions, and therefore, team 1 is not learning from previous mistakes. Furthermore, consider table 5 summarizes the regression results of the time-series analysis where the null and alternative hypotheses were as follows:

- H_0 : slope of regression line is equal to 0.
- H_a : slope of regression line is not equal to 0.

A t-test was carried out and the results showed a p-value of 0.25 which is less than the significance level which was chosen as 0.05. Thus, the null hypothesis was not rejected, indicating that the slope of the graph in figure 16 is not statistically significant.

Refer to Appendix B to view the graphs and tables for the remaining teams of Project 1. A full of assessment of the performance of team 1 is described in the next section.

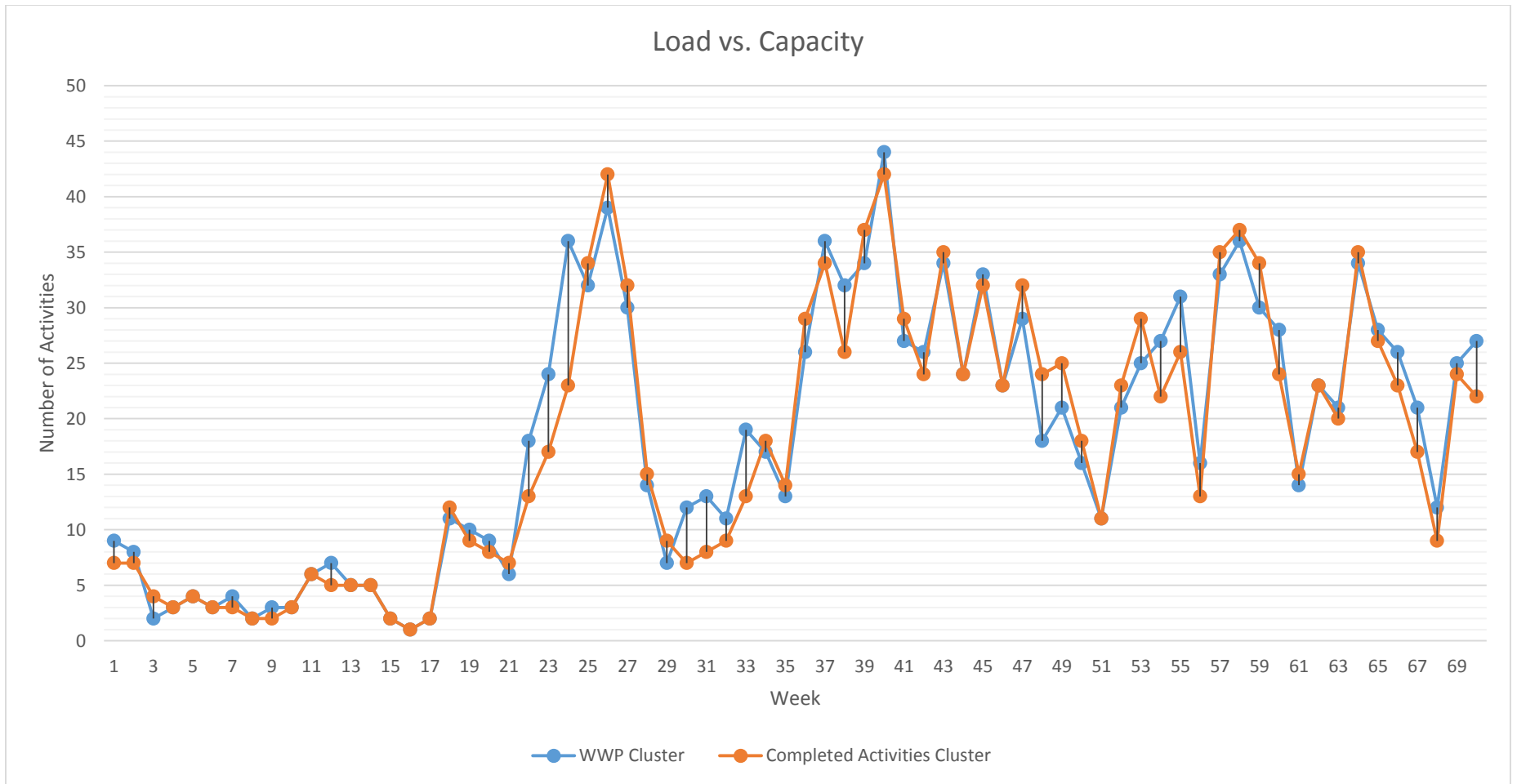


Figure 12 - P1T1: Load vs. Capacity

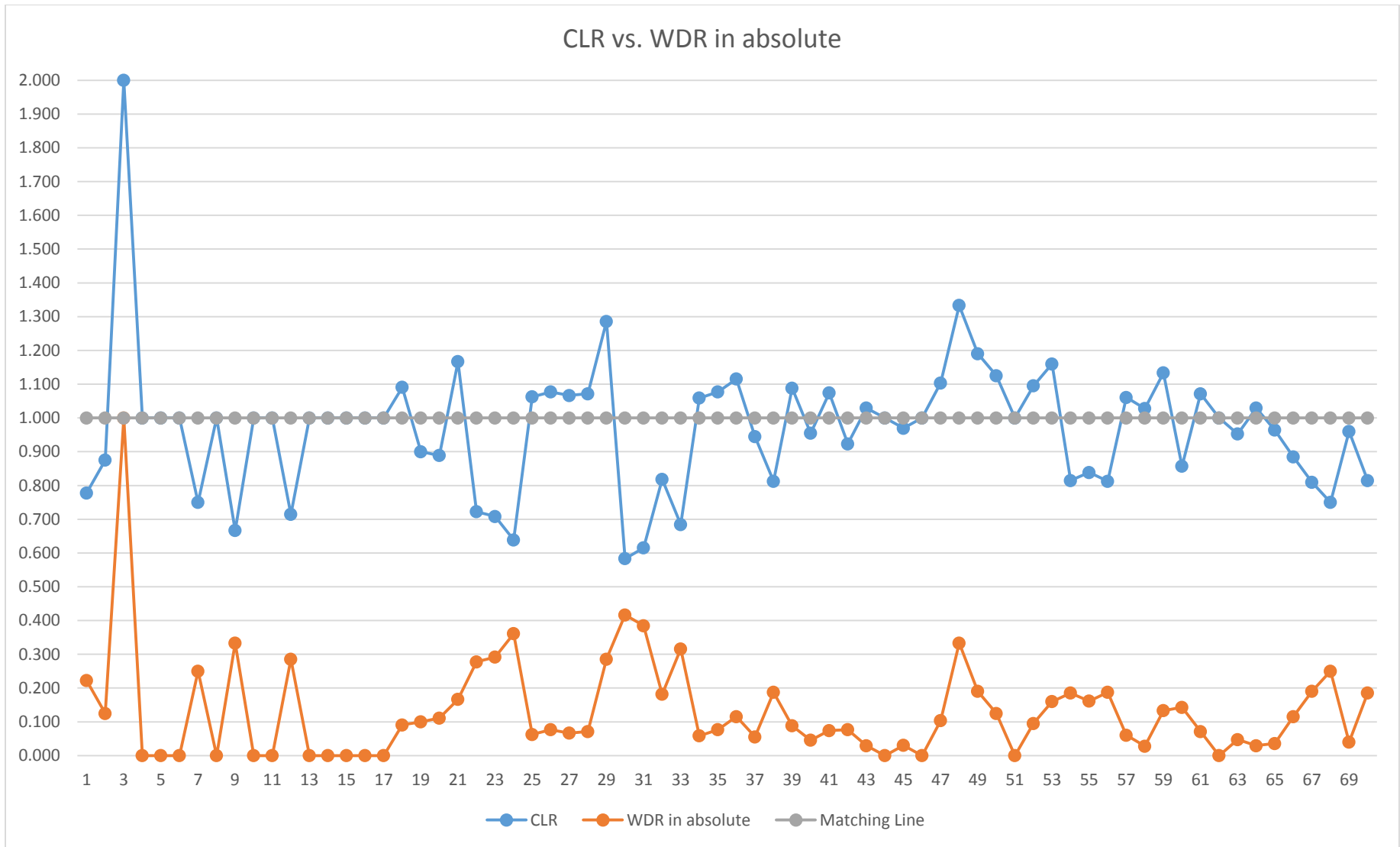


Figure 13 - PIT1: CLR and WDR in absolute

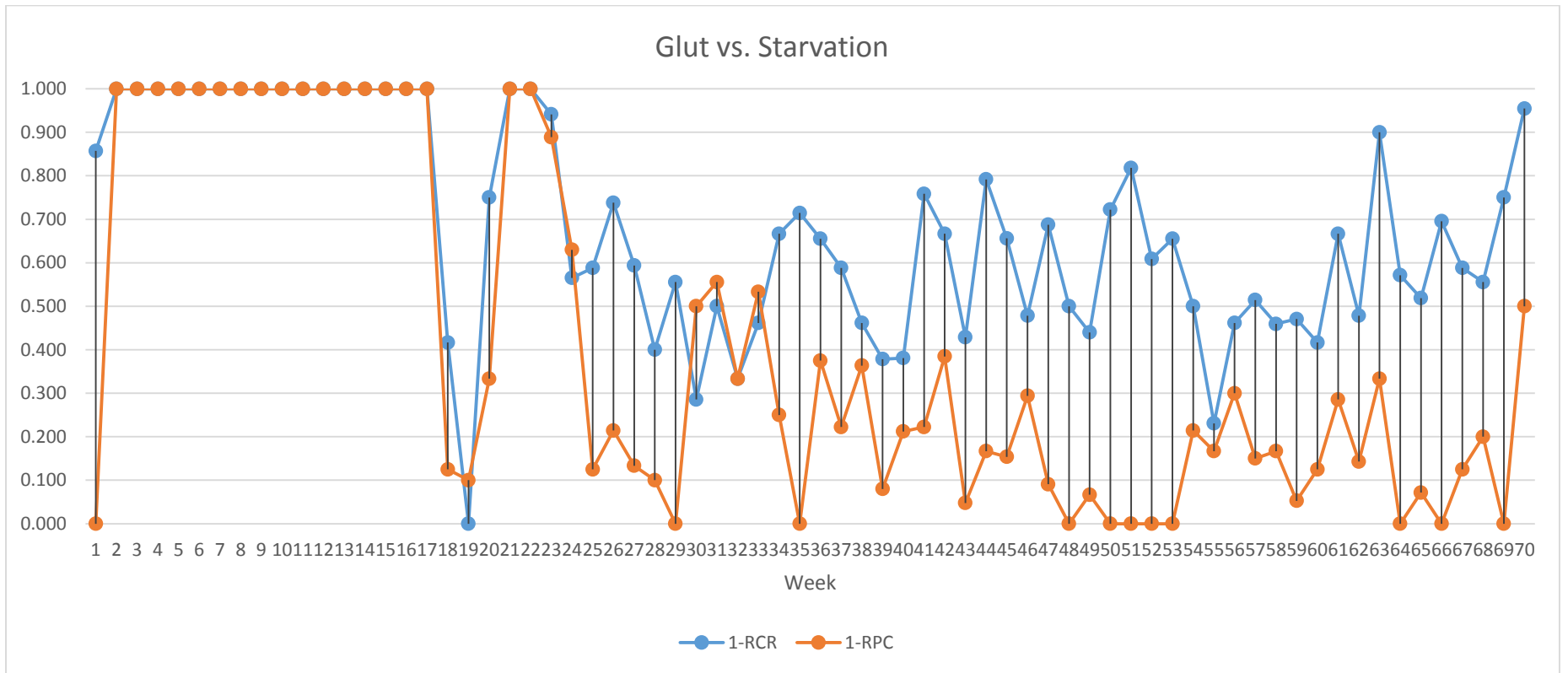


Figure 14 - PIT1: Glut vs. Starvation

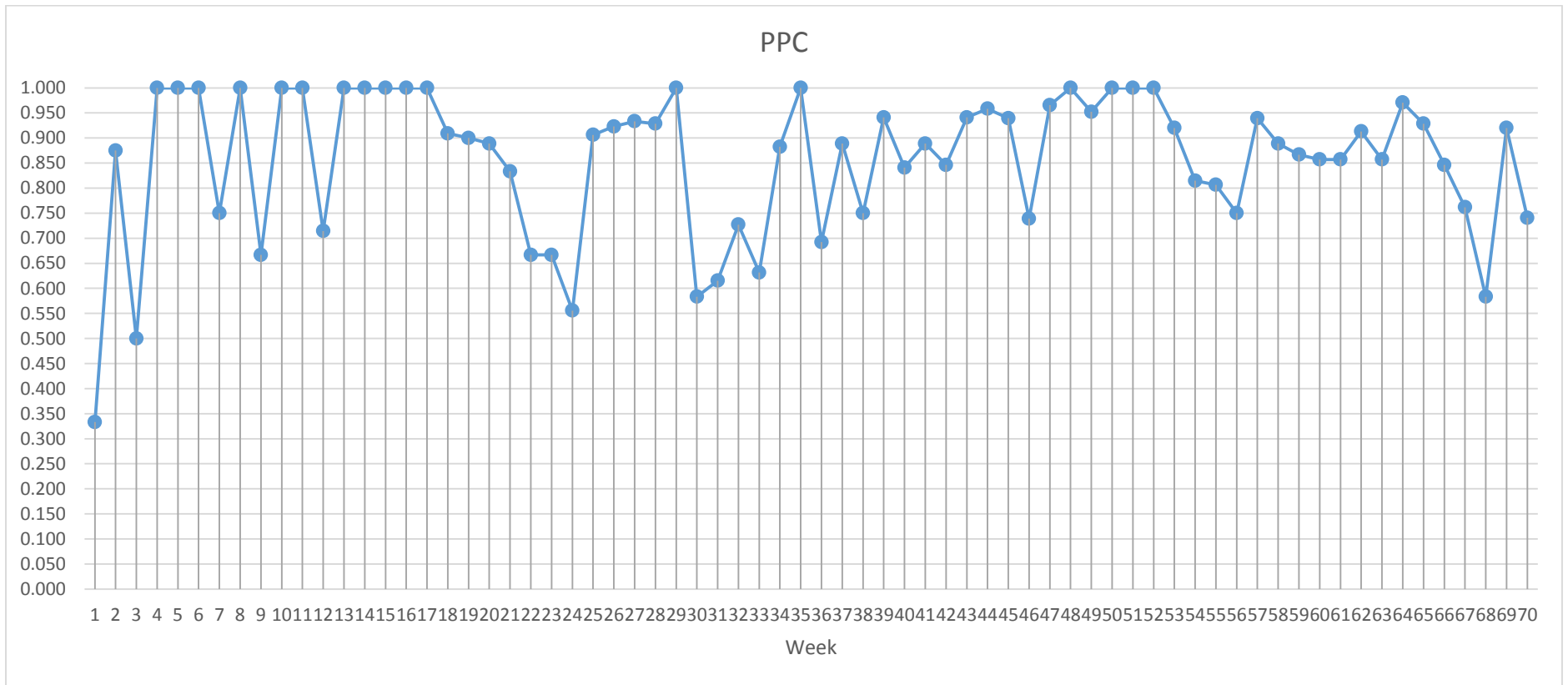


Figure 15 - PIT1: PPC

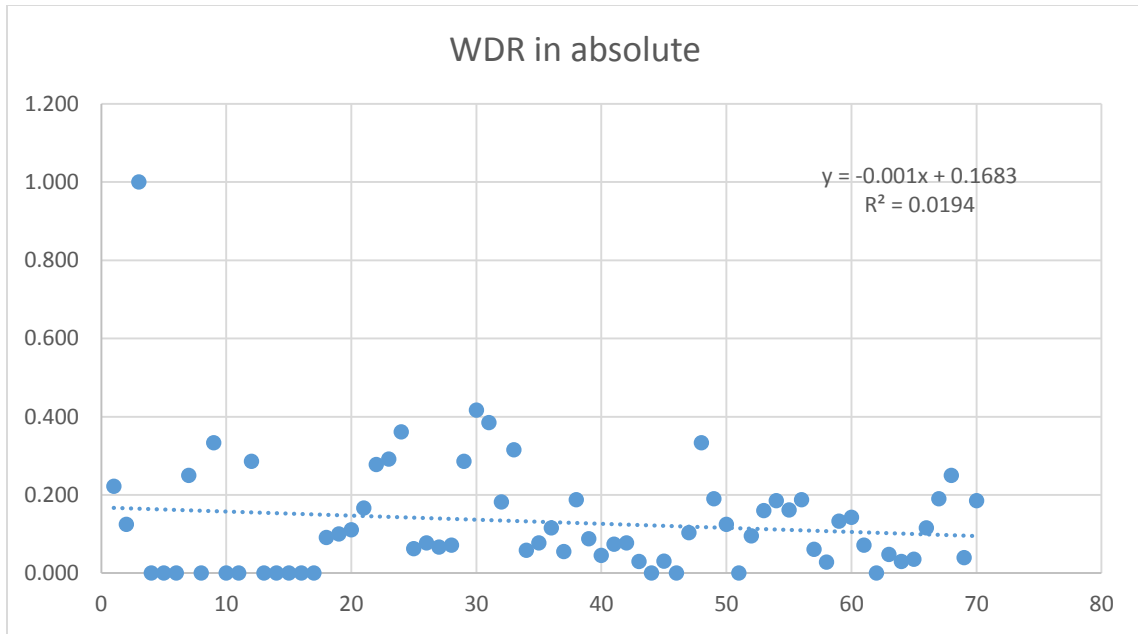


Figure 16 - P1T1: Time-Series Analysis of WDR in absolute

Table 5 - P1T1: Time-Series Regression and T-test Results

	Coefficients	Standard Error	t Stat	P-value
Intercept	0.168	0.037	4.574	0.000
Week	-0.001	0.001	-1.159	0.250

2. Project 1 – Team Comparison

Table 6 summarizes the performance of each team on Project 1. There are six columns in the table. The first column is the NTD (Normalized Team Deviation) which gives an indication of the magnitude of deviation between capacity and load for each team. The second column is the Glut/week which is the average Glut of each team (i.e. on average, what percentage of completed tasks are not critical). Similar to Glut/week, column three is the Starvation/week which is the average Starvation of each team (i.e. on average, what is the percentage of critical activities that are starving for resources each week). The fourth column is the Misallocation Factor for each team which gives an indication of the extent of misallocation of resources for each team. It is the sum of the average Glut (Glut/week) and average Starvation

(Starvation/week). The fifth column is the average PPC of each team. It gives an indication of how reliable each team is in committing and completing. The sixth column is the CLR/week which is the average CLR of each team. It indicates, on average, how close each team is to matching their chosen capacity to their available load. Notice that there are 3 colors in the table. The green color indicates the top two performing teams for a certain metric, the red color is for the two teams that have performed the worst, and the yellow color indicates the teams that are in the middle.

Team 1 has the second highest CLR/Week with an average of 0.971. This indicates that team 1 is, on average, overloading its available resources but is relatively close to matching the chosen load to the available capacity. Furthermore, team 1 seems to be in the middle when it comes to performance in terms of allocation of resources. It has a Glut/Week of 0.683 (68.3% of completed activities are non-critical) and a Starvation/Week of 0.405 (40.5% of critical activities are not completed). These two values yield a Misallocation Factor of 1.087. Team 1 also has a relatively middle value (third highest) for PPC with 85.7% of committed activities being completed per week.

Team 3 has the highest PPC 0.893 (89.3% of committed activities are being completed per week) but has also scored the highest NTD (0.157) and the farther CLR from 1 (0.104), with the largest Glut and Starvation per week with values of 0.925 and 0.435 respectively (92.5% of completed activities are non-critical and 43.5% of critical activities that are not executed). Therefore, if PPC is the only metric a team is measuring its performance, then by virtue of that team 3 is performing very well. But, since there are large deviations, then team 3 is not matching the load to the available capacity. Furthermore, the fact that there is high Glut and Starvation per week, indicates that team 3 is also misallocating the available resources.

Furthermore, if we look at team 4, it seems to have the lowest PPC (77%), largest team deviation with an NTD of 0.185, and farthest CLR from 1 (0.05). However, notice that it has a relatively average to low Starvation (28.3% of completed activities are non-critical), a relatively low Glut per week (53.3% of critical activities are not complete), and an average Misallocation Factor of 0.816.

Similarly, although team 5 seems to be performing averagely when it comes to matching load to capacity, but it seems to be second best at allocating its resources with a Misallocation Factor of 0.811. Note that Glut is 56.7% (average but third lowest) and Starvation is 24.4% (second lowest).

On the other hand, team 7 has the second highest PPC (89.7%) but seems to be performing averagely on all other fronts. This is an indication that team 7 is able to mostly execute whatever it is committing to complete each week, but may not be paying much attention to matching its load to capacity or properly allocating the available resources.

Team 8 has a near average PPC of 0.845 (84.5% of committed activities are executed per week), and a middle CLR/Week of 0.968 (i.e. on average team 8 seems to be overloading the available resources.). However, has the second lowest NTD of 0.124. Furthermore, has the lowest Starvation/Week (20.2% of critical activities are not completed per week) and the lowest Glut/Week (40.6% of completed activities are non-critical). These two values yielded the lowest Misallocation Factor of 0.608. Therefore, it could be concluded that team 8 is better at allocating its resources than at committing to completing work.

If we look at team 9, although this team has the lowest deviation (NTD = 0.118) and the closest CLR to 1 (0.991), it is still misallocating its resources since it is starving 45.3% of critical activities and wasting 84.5% of the resources availability. Moreover, team 9 also has a relatively

low PPC of 84% (2nd lowest of all the teams). Therefore, looking at the metrics related to matching the capacity and load is not enough. Teams should also monitor the allocation of the available resources.

Table 6 - Project 1 Summary

	NTD	Glut/Week	Starvation/Week	Misallocation Factor	PPC	CLR/Week
Team 1	0.131	0.683	0.405	1.087	0.857	0.971
Team 3	0.157	0.925	0.435	1.360	0.893	1.104
Team 4	0.185	0.533	0.283	0.816	0.770	0.950
Team 5	0.132	0.567	0.244	0.811	0.844	0.968
Team 7	0.125	0.835	0.357	1.191	0.897	1.035
Team 8	0.124	0.406	0.202	0.608	0.845	0.968
Team 9	0.118	0.845	0.453	1.298	0.840	0.991
Project 1	0.139	0.685	0.340	1.025	0.849	0.998
max	0.185	0.925	0.453	1.360	0.897	1.104
min	0.118	0.406	0.202	0.608	0.770	0.950

Figure 17 depicts the information summarized in Table 7. The team performing optimally would be the team with the lowest values in the 5 indicators shown on the x-axis.

From figure 17, it appears that team 8 has the lowest NTD, Glut/Week, Starvation/Week, and average Misallocation Factor. Teams 4 and 5 seem to have relatively close values and based on the graph seem to be have almost the same level of performance, although based on the previous analysis, team 5 had better overall results. On the other hand, team 4 is better at allocating its resources than teams 1, 3, 7, and 9. Furthermore, team 4 has the highest 1 – PPC (i.e. lowest PPC), but it has lower Glut/Week, lower Starvation/Week, and therefore lower Misallocation Factor than teams 3 and 7.

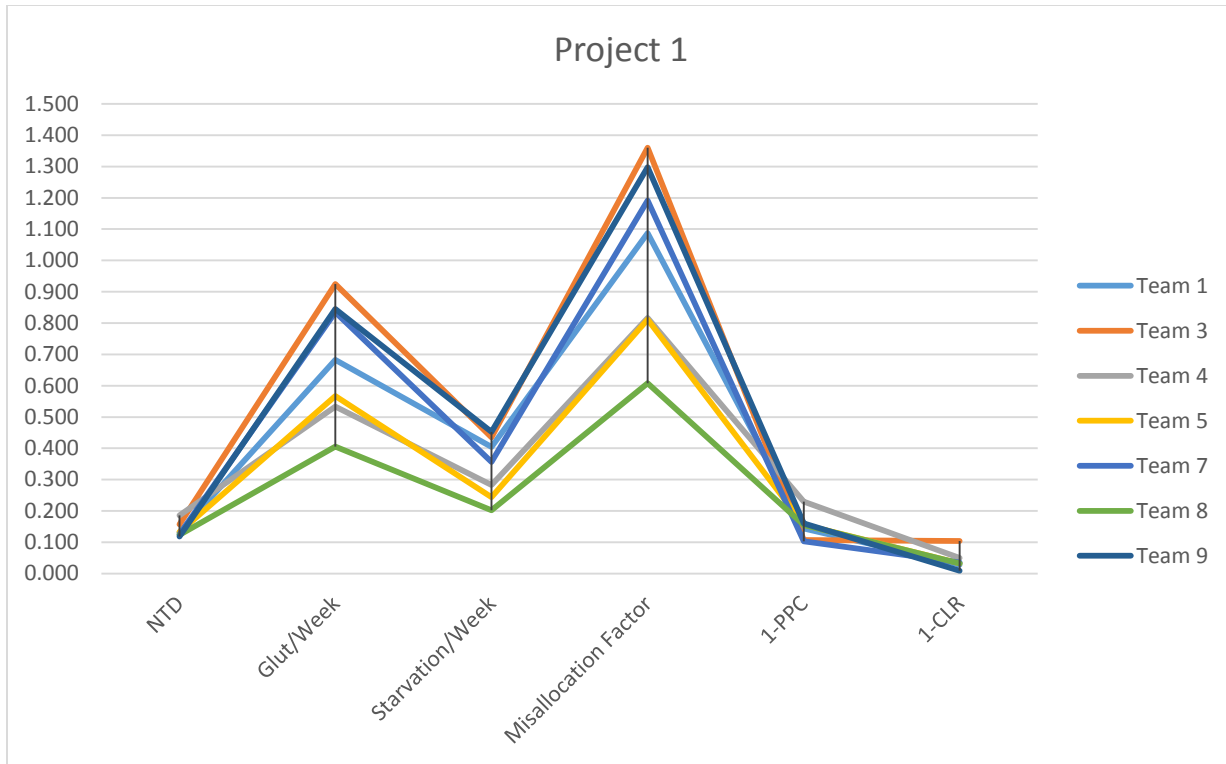


Figure 17 - Project 1 Summary

Furthermore, consider table 6 which summarizes the results of the time-series analysis of WDR in absolute for project 1. Notice that all the teams except for one (team 3) have a slope that is not statistically significant, which indicates that the teams are not learning from past mistakes, and their decisions are not correlated with time.

Table 7 - Time-Series Analysis and T-test Results for Project 1

	Team 1	Team 3	Team 4	Team 5	Team 7	Team 8	Team 9
P-Value	0.250	0.040	0.219	0.099	0.875	0.314	0.234
Slope Significance	Not signif.	Signif.	Not signif.	Not signif.	Not signif.	Not signif.	Not signif.

B. Results and Analysis of Project 2

Refer to Appendix A to view the graphs of the teams of Project 2.

1. Project 2 – Team Comparison

For the following analysis and comparison, please refer to table 8 which summarizes the performance of the teams of Project 2.

Team 1 has the largest deviation with an NTD of 0.382. It also has the largest Glut/week, Starvation/week, and thus the largest Misallocation Factor (93.1% of non-critical activities are completed when there are 53.4% critical activities that have not been executed with a Misallocation Factor of 1.465). Team 1 also has the lowest PPC of 73.4% (i.e. out of the tasks team 1 is committing every week, about 73% of these tasks are being actually executed each week). Finally, team 1 also has the farthest CLR from 1 on average with a CLR/week of 1.155. This indicates that team 1 is, on average, underloading the available resources.

Team 3 seems to be in the middle with an NTD of 0.153. It also has 0.764 Glut/week (which means that 76.4% of completed activities are non-critical), 0.338 Starvation/week (33.8% of critical activities were not executed), and a Misallocation Factor of 1.101. On average, team 3 seems to be completing 79.6% of the activities that it is committing to with a PPC of 0.796. Finally, team 3 is relatively close to matching its load to the available capacity but are generally underloading each week with an average CLR of 1.027.

Finally, the best performing team is team 4 with a very low deviation between capacity and load (NTD = 0.099). It has the lowest Glut/week with 74.8% of completed activities being non-critical, lowest Starvation/week with 26.9% of critical activities that have not been executed, and the lowest average Misallocation Factor of 1.016. Team 4 also has the lowest PPC of 79.7% (notice that all three teams have a relatively close PPC with the entire project having an average

PPC of 77.6%). Finally, team 4 seems to be matching the load to its available capacity on average with a CLR/week of 1.

Table 8 - Project 2 Summary

	NTD	Glut/Week	Starvation/Week	Misallocation Factor	PPC	CLR/Week
Team 1	0.382	0.931	0.534	1.465	0.734	1.155
Team 3	0.153	0.764	0.338	1.101	0.796	1.027
Team 4	0.099	0.748	0.269	1.016	0.797	1.000
Project 2	0.211	0.814	0.380	1.194	0.776	1.060
max	0.382	0.931	0.534	1.465	0.797	1.155
min	0.099	0.748	0.269	1.016	0.734	1.000

As can be concluded from Table 9 and can be seen in figure 18, team 1 is the worst performing team having the lowest values for all 6 indicators, while team 4 is the best performing team with the highest values for all 6 indicators. Notice from figure 18 that teams 3 and 4 are relatively close in performance. Although all three teams have close PPC, they have a large gap in the Misallocation Factor, which means that not all are properly allocating their resources.

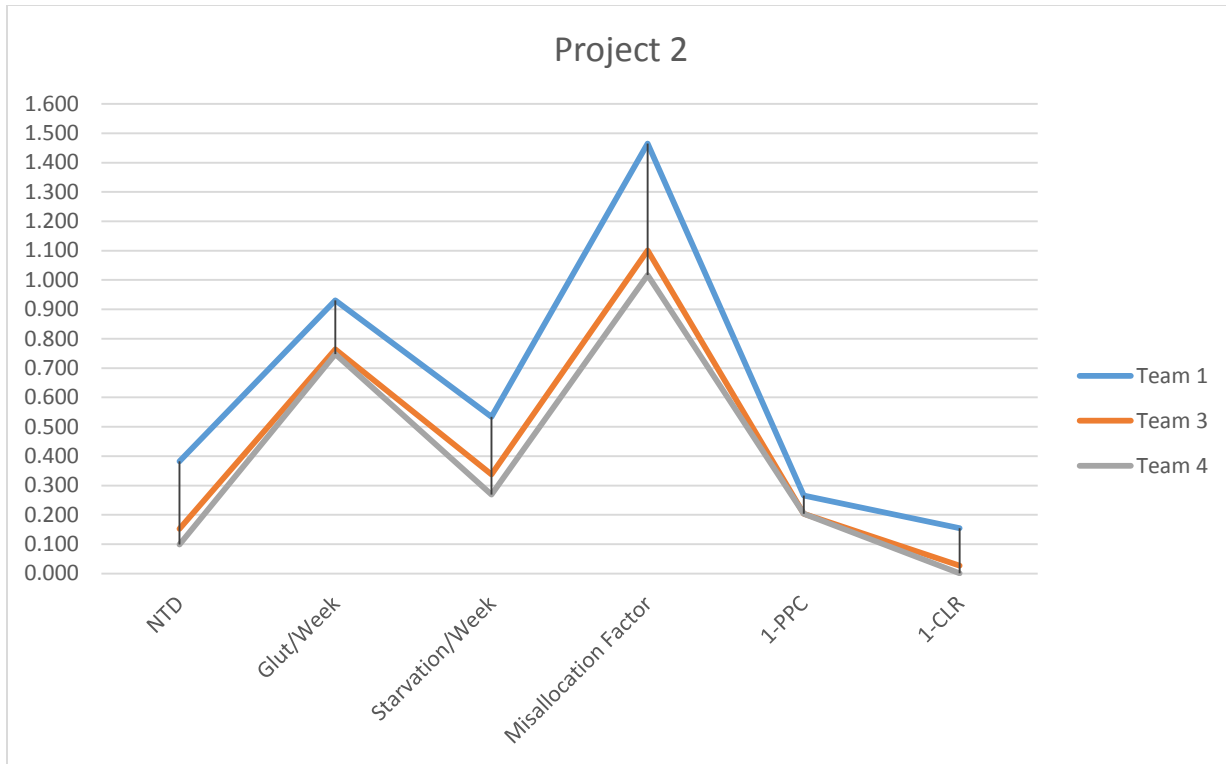


Figure 18 - Project 2 Summary

Furthermore, consider table 9 which summarizes the results of the time-series analysis of WDR in absolute for project 2. Notice that, teams 1 and 3 have a statistically significant slopes, while the slope of team 4 is not statistically significant. This means that the decisions of teams 1 and 3 may be correlated with time, while team 4 is not learning from past mistakes, and the decisions are not correlated with time.

Table 9 - Time-Series Analysis and T-test Results for Project 2

	Team 1	Team 3	Team 4
P-Value	0.014	0.000	0.225
Slope Significance	Signif.	Signif.	Not Signif.

C. Comparison of Projects 1 and 2

As previously mentioned, optimal performance is signified by the lowest possible values of the 6 indicators. Notice from Table 10 and Figure 19 that Project 1 is out-performing Project 2 with lower values in all 6 indicators.

Project 1 has a lower normalized deviation (0.139) than does Project 2 (0.211). Project 1 has 0.685 Glut/Week which means that on average, Project 1 has 68.5% of completed activities that are non-critical, whereas Project 2 has a much higher Glut/Week, with 81.4% of completed activities being non-critical. When looking at Starvation/Week, Project 1 has on average 34% of critical activities that are not being executed, and Project 2 has a relatively close Starvation/Week with 38% of critical activities that remain uncomplete each week. This in turn will yield a lower Misallocation Factor for Project 1 (1.025) than Project 2 (1.194). Furthermore, Project 1 has a PPC of 0.849 which indicates that on average, 84.9% of committed activities are being executed each week, whereas Project 2 has a lower PPC of 0.776, which means that 77.6% of committed activities are being executed per week. Finally, Project 1 also out-performs Project 2 when it comes to matching load to capacity. It turns out that Project 1 seems to be, on average, overloading its resources with a CLR of 0.998, whereas Project 2 seems to be, on average, underloading its available resources with a CLR of 1.060. Although one project seems to overload and the other underload, neither of them is able to match the load to capacity, although Project 1 seems to have a CLR closer to 1, which means that Project 1 is closer to matching the load to its existing capacity.

Table 10 - Project 1 vs. Project 2

	NTD	Glut/Week	Starvation/Week	Misallocation Factor	PPC	CLR
Project 1	0.139	0.685	0.340	1.025	0.849	0.998
Project 2	0.211	0.814	0.380	1.194	0.776	1.060

Consider figure 19 below. The graph summarizes the analysis above by showing that Project 1 has lower values of NTD, Glut/Week, Starvation/Week, Misallocation Factor, 1-PPC, and 1-CLR. Note that 1-PPC and 1-CLR are used instead of PPC and CLR respectively to visually show which Project is better. If a high PPC is ideal, then 1-PPC needs to be low. Similarly, if a CLR closest to 1 is ideal, then 1-CLR in absolute value needs to be low.

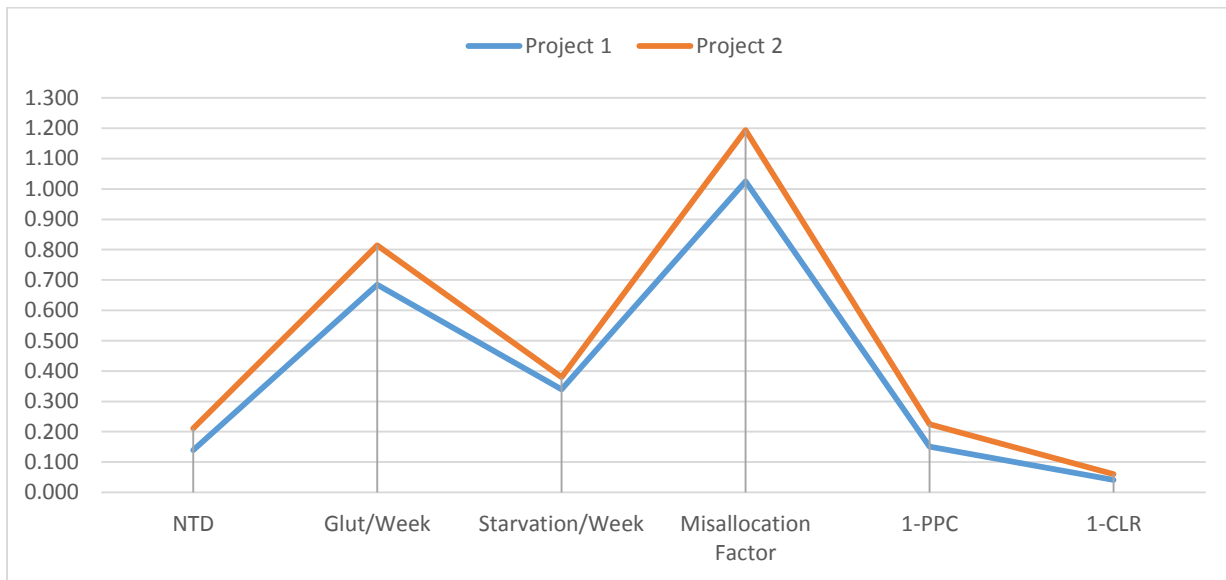


Figure 19 - Project 1 vs. Project 2

CHAPTER VI

CONCLUSION AND FUTURE WORK

A. Conclusion

The need for proper and reliable planning is essential for project success. Capacity planning has received good attention in the construction community but few metrics exist to assess its performance. Since it is impossible to improve what cannot be measured, new capacity planning metrics, that will help visualize and understand the current state of capacity planning on construction projects, were developed in this study. Is there an overloading or under loading of resources? These new metrics will help in informing planners and last planners about the status of load vs. capacity, the matching between the two, and the reliability of capacity planning on a project.

Seven primary metrics and four secondary metrics related to capacity planning that can be measured on a weekly basis were introduced in this study. The CLR (capacity to load ratio) measures the capacity available (tasks actually completed) versus the chosen load (tasks committed to be completed that week); the CLR man-hrs is the same as the previous metric except that it measures man-hours (i.e. man-hours actually expended vs. man-hours required to complete the committed tasks). The third primary metric is RCR which gives the planners an indication of how many tasks were required/are critical out of all those executed this week. The fourth primary metric is RPC which depicts the percentage of critical tasks completed this week, and the fifth primary metric is the RPC man-hrs (which is the same as the RPC but instead of using the number of activities, the number of man-hours is used). The last two primary metrics

are WD which is deviation from the WWP, and WDR which is the normalized version of the WD (mainly created for comparison across multiple weeks and/or across different projects).

The four secondary metrics created are the Glut which quantifies the percentage of completed activities that are non-critical activities. Starvation which is the percentage of critical activities that have not been executed and are starving for resources, and the Misallocation Factor which is the sum of the Glut and Starvation, and this helps give an idea of the extent of the misallocation of the resources. Finally, the fourth secondary metric is the Normalized Team Deviation (NTD) which is the average of WDR in absolute over the number of weeks.

These primary and secondary metrics were created and applied to two sets of real pre-processed data from two on-going projects in the US. Note however that the metrics related to man-hours were not computed for lack of sufficient information on the man-hours. After analysing the results of each project alone and then comparing the two projects, it turned out that Project 1 out-performed Project 2.

This study has shown that firstly, project teams do not apply capacity planning techniques. When we see values of CLR that are greater than 1, then teams are underloading their available resources and are therefore not committing enough tasks to the WWP. On the other hand, when we see values of CLR that are smaller than 1, then teams are overloading the available resources and are therefore committing too many activities to the WWP. As was concluded from the graphs displayed in this study, teams on projects are constantly either underloading or overloading their resources. Furthermore, even if the CLR, on average, is close to 1, some teams experienced large deviations.

Secondly, this study has proven that a lot of the time, teams rely on PPC as the only performance metric. If PPC is high, then this team is performing optimally because it is able to

complete what it has promised to complete regardless of any other indication of shortcomings. These results showed that although some teams may have a high PPC, they are not allocating their resources properly.

This leads to another conclusion that can be drawn from this research, and that is that teams are knowledgeable of the existence of the critical tasks and they plan for them accordingly, but do not actually execute them. The results showed that although critical tasks are tracked throughout the project, and are committed to the WWP, a percentage of these critical activities seems to be left unexecuted. From the Starvation and Glut metrics, it was derived that teams are misallocating their resources. Instead of allocating available resources to critical tasks that a team has committed to complete, it seems that the allocation of resources is either not prioritized based on criticality or is assigned at random. In either case, some critical activities are left starving for resources while non-critical activities are executed prior.

On the other hand, some teams focus on Glut and Starvation without realizing they do so, but this comes at the expense of PPC. In other words, some teams try to execute as many critical activities as possible and end up with unreliable promising due to the low PPC, the impact of which should be studied in future research.

Another conclusion can be made from this research, which is that although some teams have a CLR close to 1, which means that they are close to matching their load to the available capacity, they seem to neglect critical activities which in turn results in high Starvation and Glut. When a team is focused on choosing a load to match to the available capacity, it seems to forget about properly allocating the resources to critical activities. In other words, even if teams are able to avoid overloading or underloading the resources, they still aren't paying attention to the

fact that some critical activities are not being executed even when the resources are available to do so since the teams are able to execute non-critical activities first.

From the time-series analysis implemented on the Weekly Deviation Ratio (WDR) in absolute, it showed that there was little to no correlation with the deviation over time with most teams displaying a slope that is not statistically significant, which means that most teams are not learning from their mistakes.

Finally, this study has shown the existence of a mismatch problem, the need for proper planning skills, and hence the need for capacity planning metrics. If these metrics are used on a project on a weekly basis, people will be aware of their capacity planning waste, which in turn will aid in finding solutions to boost performance. However, none of these new capacity planning metrics, or previous performance metrics, is a standalone metric. They all need to be calculated together, monitored together, more importantly analysed together in order to get a clear picture of the state of planning on a project.

Thus, the objectives set in the beginning of this study were met. The first objective which was to develop metrics to better visualize the state of capacity planning was achieved. Seven primary metrics and four secondary metrics were created, and developed. The second objective which was to apply the metrics to understand the load-capacity mismatch problem was achieved. The metrics were applied to the two projects, and the results were analysed. The results confirmed the significance of these metrics, and proved their ability to visualize the problems in capacity planning.

B. Future Work

Further research on this topic and the testing of all the metrics introduced on this study to prove their reliability in attempting to visualize the problem of capacity planning is quintessential, is required. Questions such as the following need to be explored. Is there a correlation between these capacity planning metrics and other performance metrics? Future study should focus on gathering all required data such that all the metrics can be calculated and studied (including the metrics related to man-hours). Since this research was a retrospective study and the metrics were not calculated on the project, future studies need to calculate and track these metrics on a weekly basis in parallel with the project to see how the tracking of these metrics impacts performance, if it impacts performance. In other words, if these metrics were placed on dashboard and were continuously and regularly monitored, will the teams perform better, and consequently, will the project perform better?

REFERENCES

- Aziz, R. and Hafez, S. (2013). Applying lean thinking in construction and performance improvement. *Alexandria Engineering Journal*, 52(4), pp.679-695.
- Ballard, G. (2000). *The Last Planner System of Production Control*. Ph.D. University of Birmingham.
- Ballard, G. and Howell, G. (1998). Shielding Production: Essential Step in Production Control. *Journal of Construction Engineering and Management*, 124(1), pp.11-17.
- Ballard, G., Kim, Y., Jang, J. and Liu, M. (2007). *Roadmap to Lean Implementation at Project Level*. Research Report 234-11. Austin, Texas: Construction Industry Institute, The University of Texas at Austin.
- Ben-Haim, Y. and Laufer, A. (1998). Robust Reliability of Projects with Activity-Duration Uncertainty. *Journal of Construction Engineering and Management*, 124(2), pp.125-132.
- Bhaidani, N., Rybkowski, Z., Smith, J., Choudhury, I. and Hill, R. (2016). Percent Planned Complete: Development and Testing of a Simulation to Increase Reliability on Scheduling. In: Proc. 24th Ann. Conf. of the Int'l. Group for Lean Construction. pp.33-42.
- Damci, A. and Polat, G. (2014). Impacts of different objective functions on resource leveling in construction projects: a case study. *Journal of Civil Engineering and Management*, 20(4), pp.537-547.
- Damci, A., Arditi, D. and Polat, G. (2013). Resource Leveling in Line-of-Balance Scheduling. *Computer-Aided Civil and Infrastructure Engineering*, 28(9), pp.679-692.
- Dvir, D., Raz, T. and Shenhar, A. (2003). An empirical analysis of the relationship between project planning and project success. *International Journal of Project Management*, 21(2), pp.89-95.

- El-Rayes, K. and Jun, D. (2009). Optimizing Resource Leveling in Construction Projects. *Journal of Construction Engineering and Management*, 135(11), pp.1172-1180.
- González, V., Alarcón, L. and Molenaar, K. (2009). Multiobjective design of Work-In-Process buffer for scheduling repetitive building projects. *Automation in Construction*, 18(2), pp.95-108.
- González, V., Alarcón, L., Maturana, S., Mundaca, F. and Bustamante, J. (2010). Improving Planning Reliability and Project Performance Using the Reliable Commitment Model. *Journal of Construction Engineering and Management*, 136(10), pp.1129-1139.
- Gupta, A., Gonzalez, V. and Miller, G. (2012). Understanding the Relationship between Productivity and Buffers in Construction: A Simulation-Based Case. In: *20th Annual Conference of the International Group on Lean Construction*.
- Hamilton, M. and Gibson, G. (1996). Benchmarking Preproject Planning Effort. *Journal of Management in Engineering*, 12(2), pp.25-33.
- Hamzeh, F. and Langerud, (2011). Using Simulation to Study the Impact of Improving Lookahead Planning on the Reliability of Production Planning. In: *The 2011 Winter Simulation Conference*. pp. 3436-3447.
- Hamzeh, F., Ballard, G. and Tommelein, I. (2012). Rethinking Lookahead Planning to Optimize Construction Workflow. *Lean Construction Journal*, (2012), pp.15-34.
- Hamzeh, F. R., Zankoul, E., and Rouhana, C. (2015) “How can ‘tasks made ready’ during lookahead planning impact reliable workflow and project duration?” *Construction Management and Economics*, Taylor and Francis, pp 243-258
- Junnonen, J. and Seppanen, O. (2004). Task Planning as a Part of Production Control. In: *The 12th Annual Conference of the International Group for Lean Construction*. pp. 1-11.

- Kastor, A. and Sirakoulis, K. (2009). The effectiveness of resource levelling tools for Resource Constraint Project Scheduling Problem. *International Journal of Project Management*, 27(5), pp.493-500.
- Khattab, M. and Søyland, K. (1996). Limited-resource allocation in construction projects. *Computers & Industrial Engineering*, 31(1-2), pp.229-232.
- Kim, S. and Kim, Y. (2012). Workforce information database system to support production planning in construction projects. *Journal of Civil Engineering and Management*, 18(6), pp.867-878.
- Kim, S., Kim, Y. and Park, C. (2008). Introduction of Workforce Database System for Effective Production Planning. In: *The 16th Annual Conference of the International Group for Lean Construction*. pp. 833-838.
- Koulinas, G. and Anagnostopoulos, K. (2013). A new tabu search-based hyper-heuristic algorithm for solving construction leveling problems with limited resource availabilities. *Automation in Construction*, 31, pp.169-175.
- Lee, S., Peña-Mora, F. and Park, M. (2006). Reliability and Stability Buffering Approach: Focusing on the Issues of Errors and Changes in Concurrent Design and Construction Projects. *Journal of Construction Engineering and Management*, 132(5), pp.452-464.
- Lindhard, S. and Wandahl, S. (2012). On The Road to Improved Scheduling - Fitting Activities to Capacity. In: *RICS COBRA 2012*. pp. 1604-1612.
- Meredith, J. (1998). Building Operations Management Theory through Case and Field Research. *Journal of Operations Management*, 16, pp. 441-454.
- Park, M. and Peña-Mora, F. (2004). Reliability Buffering for Construction Projects. *Journal of Construction Engineering and Management*, 130(5), pp.626-637.

- Ponz-Tienda, J., Salcedo-Bernal, A., Pellicer, E. and Benlloch-Marco, J. (2017). Improved Adaptive Harmony Search algorithm for the Resource Leveling Problem with minimal lags. *Automation in Construction*, 77, pp.82-92.
- Rouhana, C. and Hamzeh, F. (2016). An ABC Approach to Modelling the Emergence of 'New Tasks' in Weekly Construction Planning. *Lean Construction Journal*, pp.35-56.
- Sakamoto, M., Horman, M. and Thomas, H. (2002). A Study of the Relationship between Buffers and Performance in Construction. In: *The 10th Annual Conference of the International Group for Lean Construction*.
- Serrador, P. and Turner, R. (2015). What is Enough Planning? Results from a Global Quantitative Study. *IEEE Transactions on Engineering Management*, 62(4), pp.462-474.
- Shehata, M.E. and El-Gohary, K.M. (2011). Towards improving construction labor productivity and projects' performance. *Alexandria Engineering Journal*, 50(4), pp.321-330.
- Stuart, I., McCutcheon, D., Handfield, R., McLachlin, R., Samson, D. (2002). Effective Case Research in Operations Management: A Process Perspective. *Journal of Operations Management*, 20, pp. 419-433.
- Tommelein, I., Riley, D. and Howell, G. (1998). Parade Game: Impact of Work Flow Variability on Succeeding Trade Performance. In: *The 6th Annual Conference of the International Group for Lean Construction*.
- vPlanner. (2017). What is vPlanner. [online] Available at: <http://www.myvplanner.com/vsps/> [Accessed 5 Jun. 2017].
- Yin, R. (2003). Case Study Research: Design Methods. 3rd ed. Thousand Oaks, CA: Sage Publications.

APPENDIX A

STEP-BY-STEP MANUAL

Note that these metrics can be used by any company. Even companies that do not have access to the vPlanner software can still benefit from these metrics. All they should do is gather the required data on a weekly basis and enter the collected information in a table similar to the one shown in figure 20 below. The following steps can be followed:

Every week,

1. Sum all the New activities at the start of the week (column K).
2. Sum all the activities on the Backlog at the start of the week (column L).
3. Sum all the activities that are committed to the WWP at the start of the week (column M).
4. Sum all the activities that make up the total activities cluster at the start of the week (column J = columns K+L+M).
5. Sum all the completed activities at the end of the week (column N).
6. Make sure to track which activities are critical and which are not.
7. Sum the critical activities at the start of the week (column R).
8. Sum the critical activities that have been completed at the end of the week (column S).
9. Sum the activities that are New and have been completed at the end of the week (column O).
10. Sum the activities that were committed to the WWP and have been completed at the end of the week (column P).
11. Calculate the metrics using the collected data and monitor the project performance.

A	B	J	K	L	M	N	O	P	Q	R	S	T	U	V	W	X	Z	AA
		Activity Clusters					PPC			Critical		Metrics					Waste	Starvation
Week	WWP Start Date	Total Activities Cluster	New Activities Cluster	Completed Backlog Cluster	WWP Cluster	Completed Activities Cluster	Completed New	Completed from WWP	PPC	Critical Activities	Completed Critical Activities	CLR	RCR	RPC	WD	WDR	1-RCR	1-RPC

Figure 20 - Sample Table for Data Collection

APPENDIX B

RESULTS AND GRAPHS

Project 1:

Team 3 (P1T3):

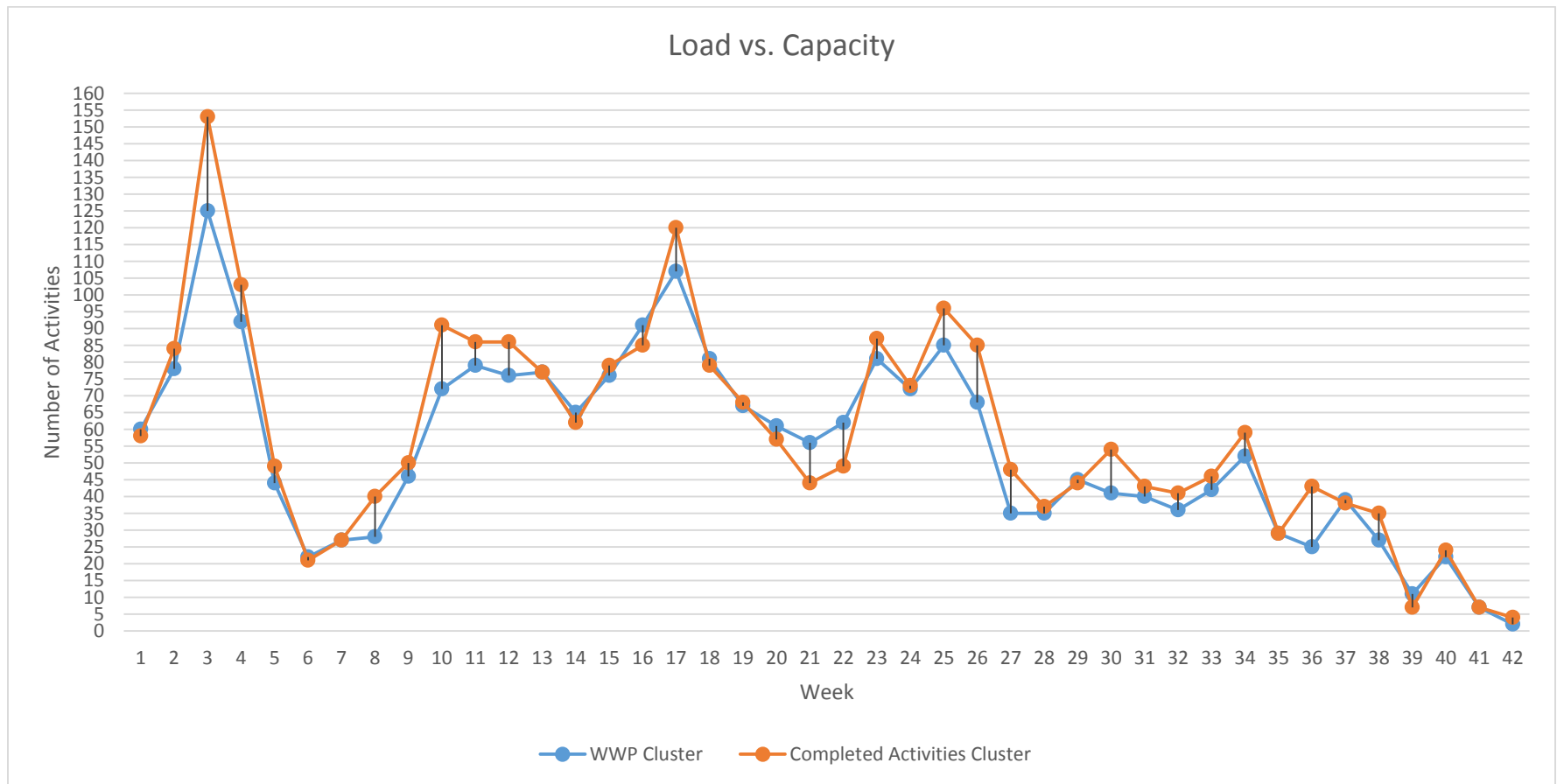


Figure 21 - P1T3: Load vs. Capacity

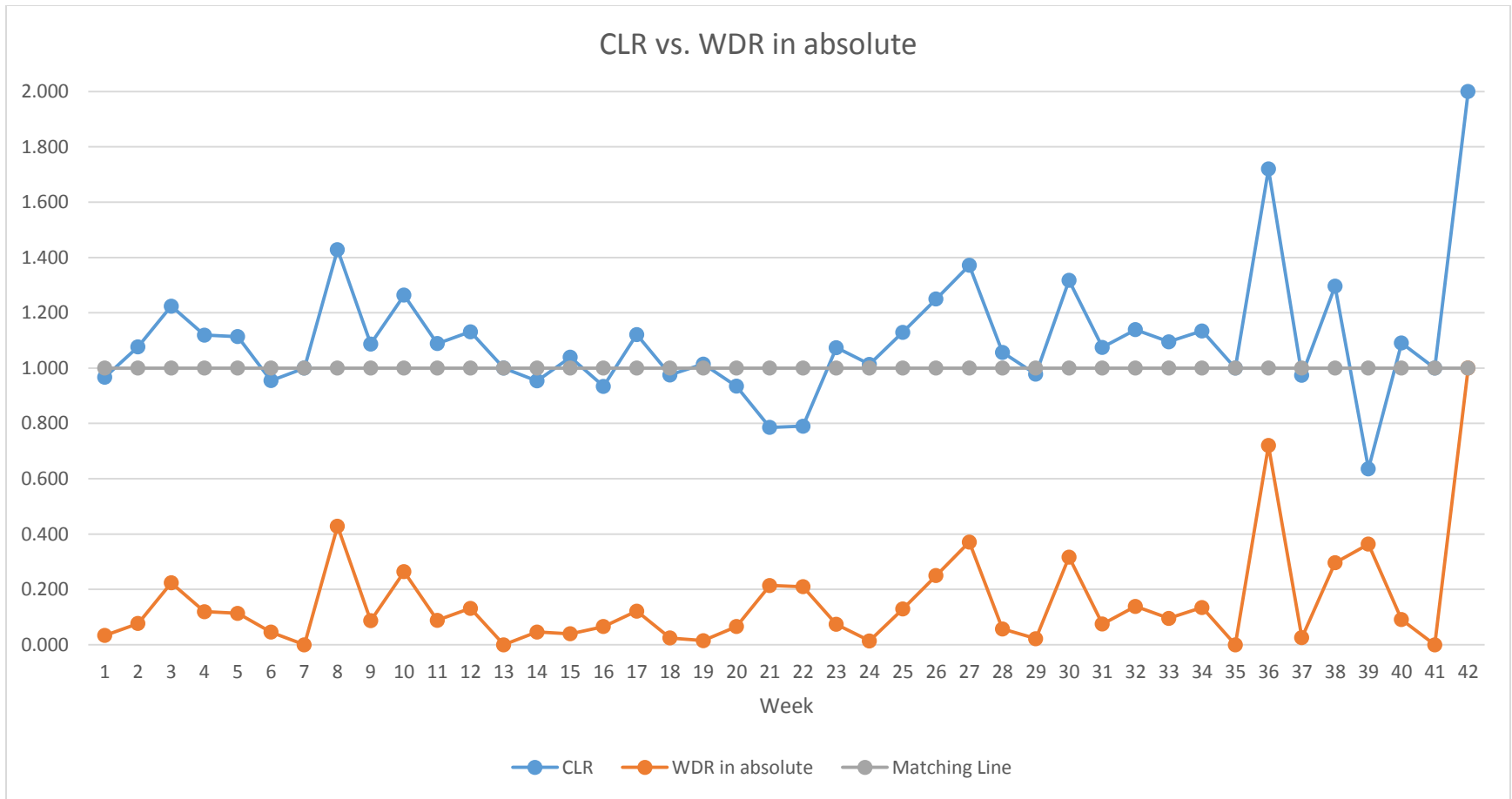


Figure 22 - P1T3: CLR vs. WDR in absolute

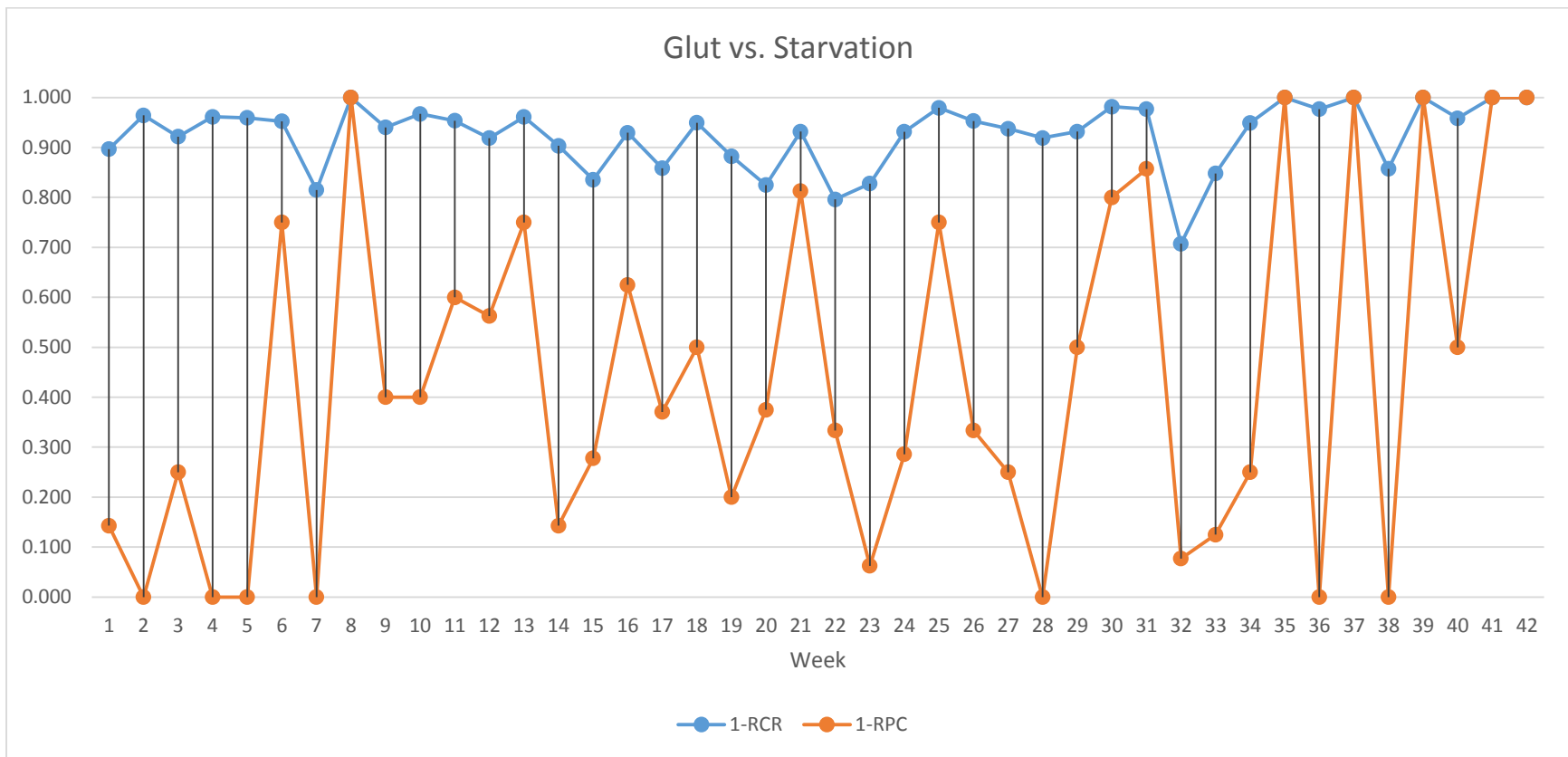


Figure 23 - P1T3: Glut vs. Starvation

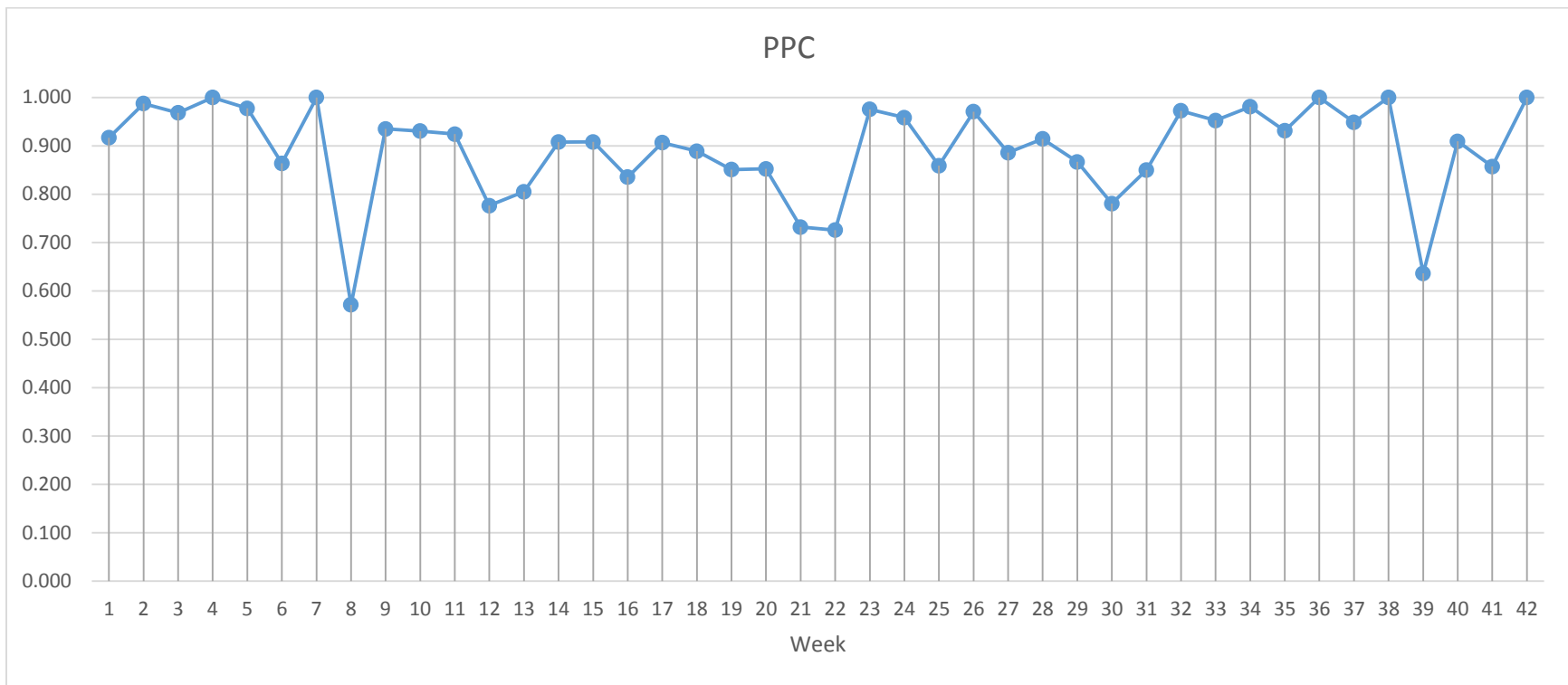


Figure 24 - P1T3: PPC

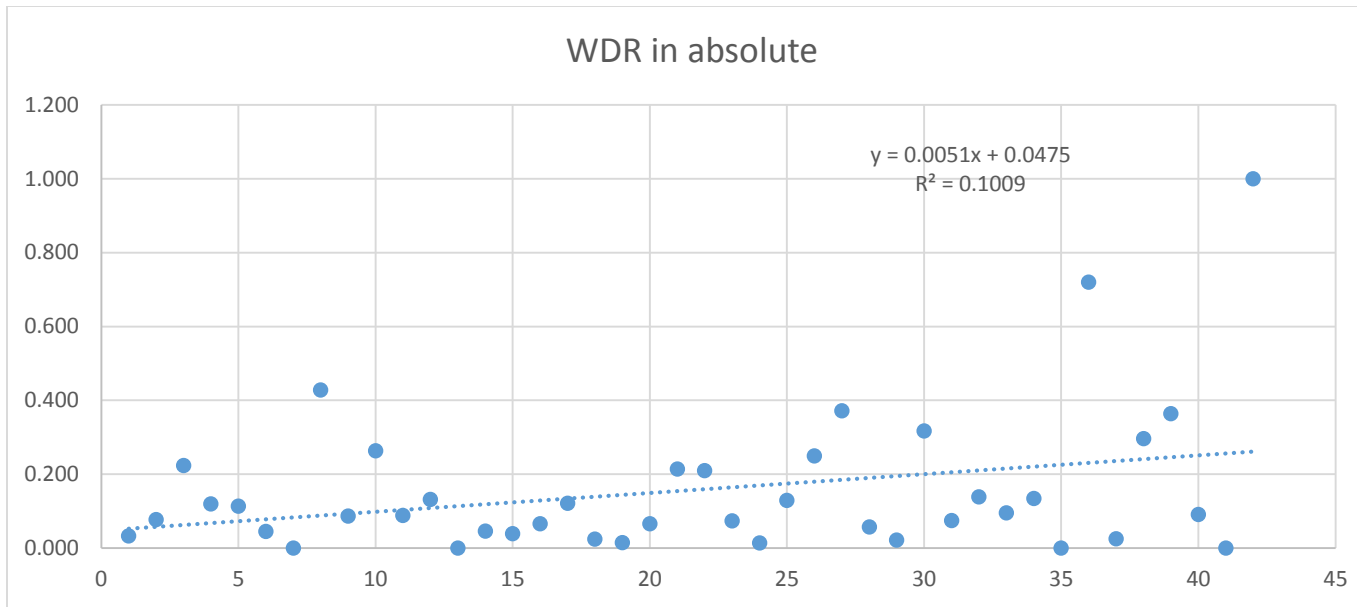


Figure 25 - P1T3: Time-Series Analysis of WDR in absolute

Table 11 - P1T3: Time-Series Regression and T-test Results

	Coefficients	Standard Error	t Stat	P-value
Intercept	0.048	0.059	0.802	0.427
Week	0.005	0.002	2.119	0.040

Team 4 (P1T4):

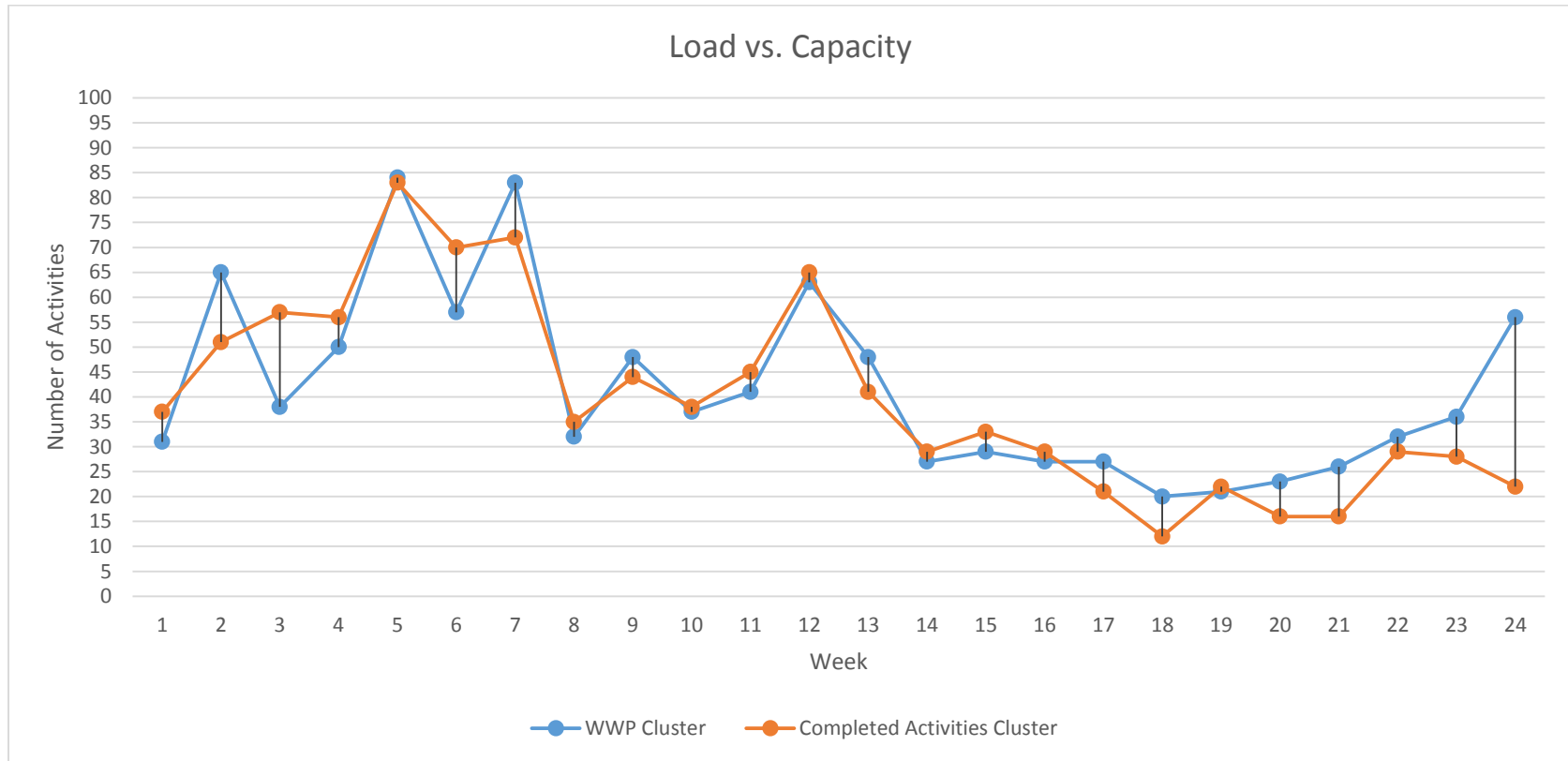


Figure 26 - P1T4: Load vs. Capacity

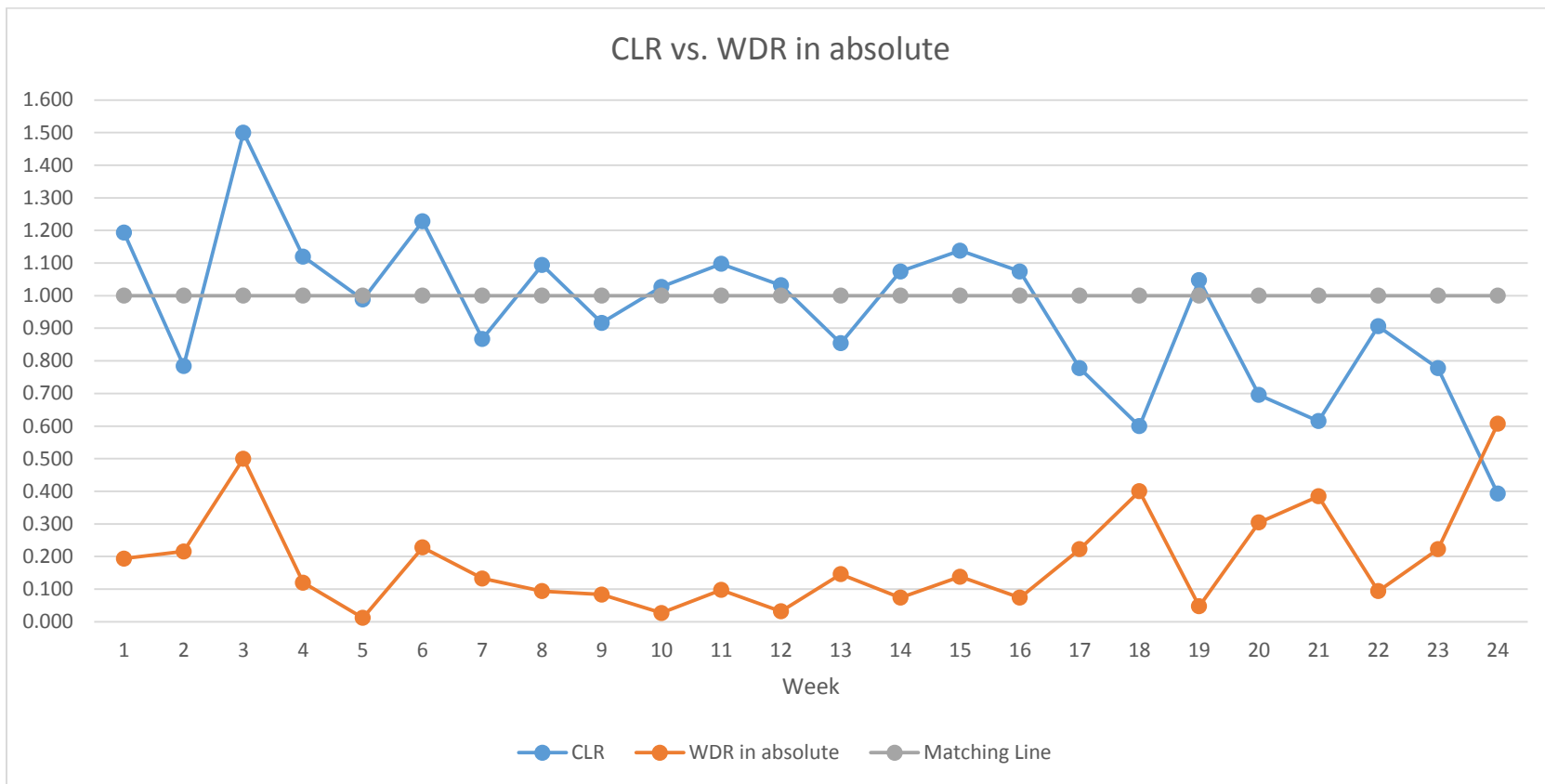


Figure 27 - PIT4: CLR vs. WDR in absolute

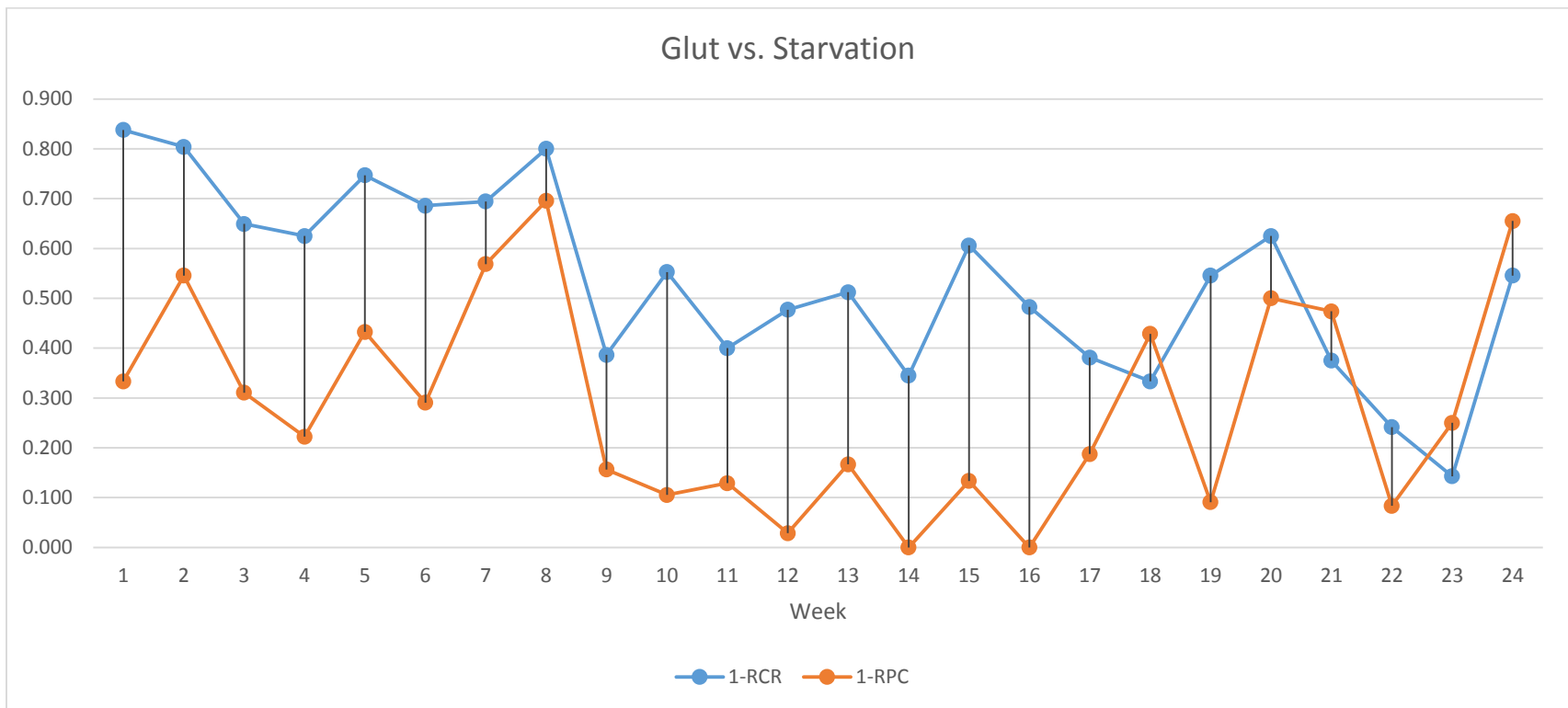


Figure 28 - P1T4: Glut vs. Starvation

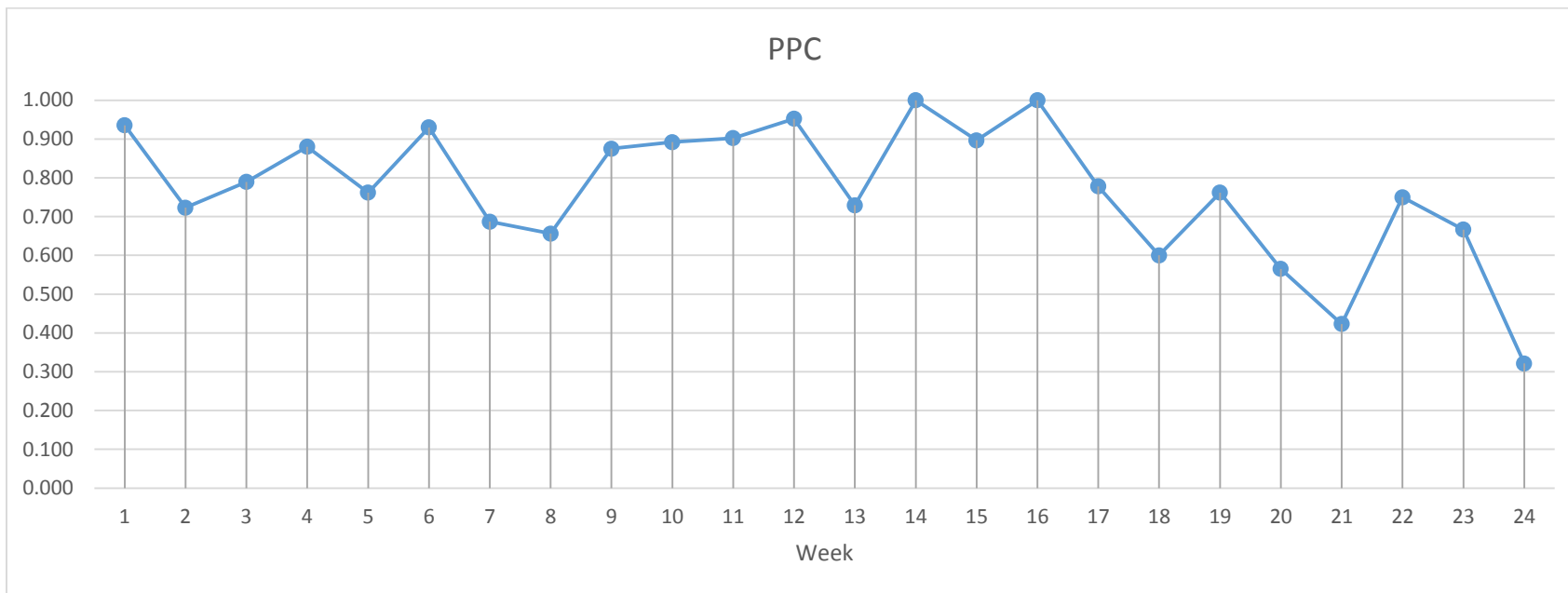


Figure 29 - PIT4: PPC

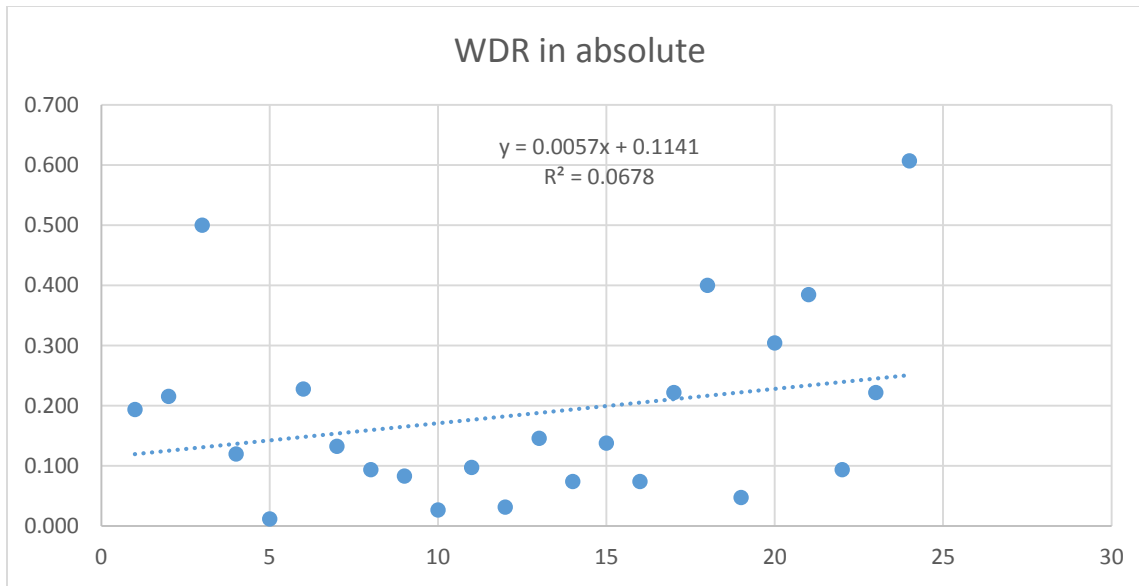


Figure 30 - P1T4: Time-Series Analysis of WDR in absolute

Table 12 - P1T4: Time-Series Regression and T-test Results

	Coefficients	Standard Error	t Stat	P-value
Intercept	0.114	0.064	1.773	0.090
Week	0.006	0.005	1.265	0.219

Team 5 (P1T5):

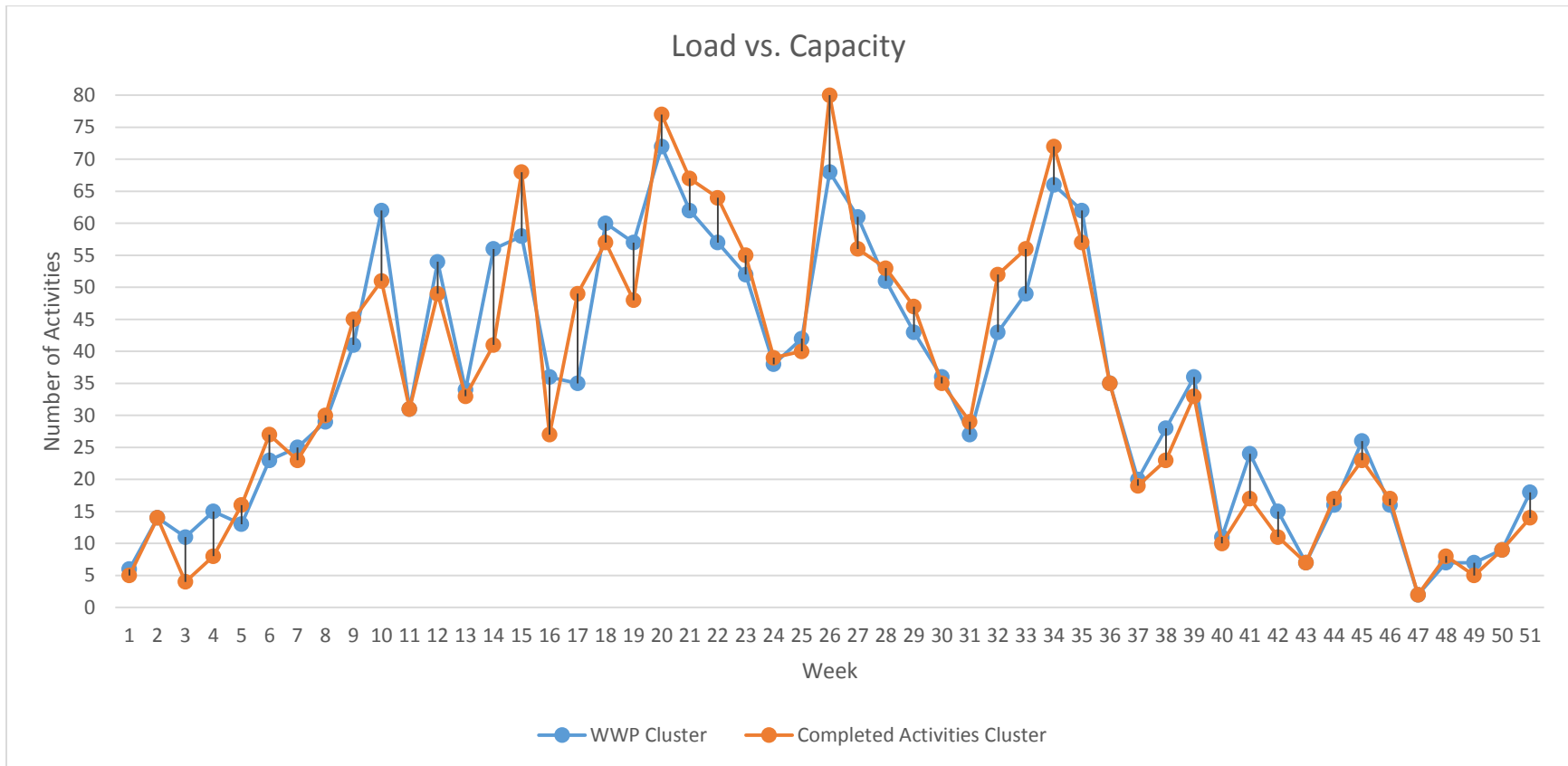


Figure 31 - P1T5: Load vs. Capacity

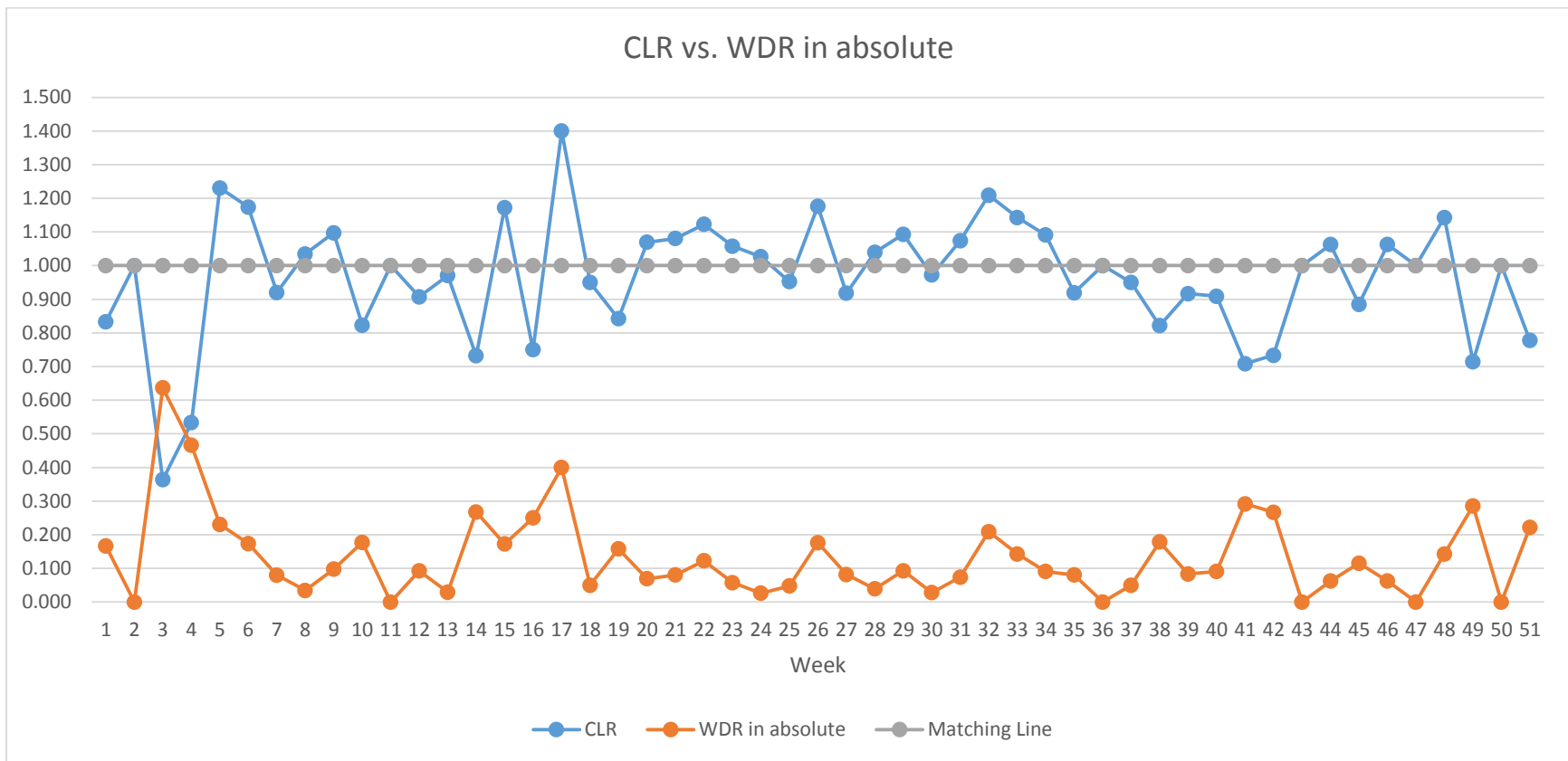


Figure 32: PIT5: CLR vs. WDR in absolute

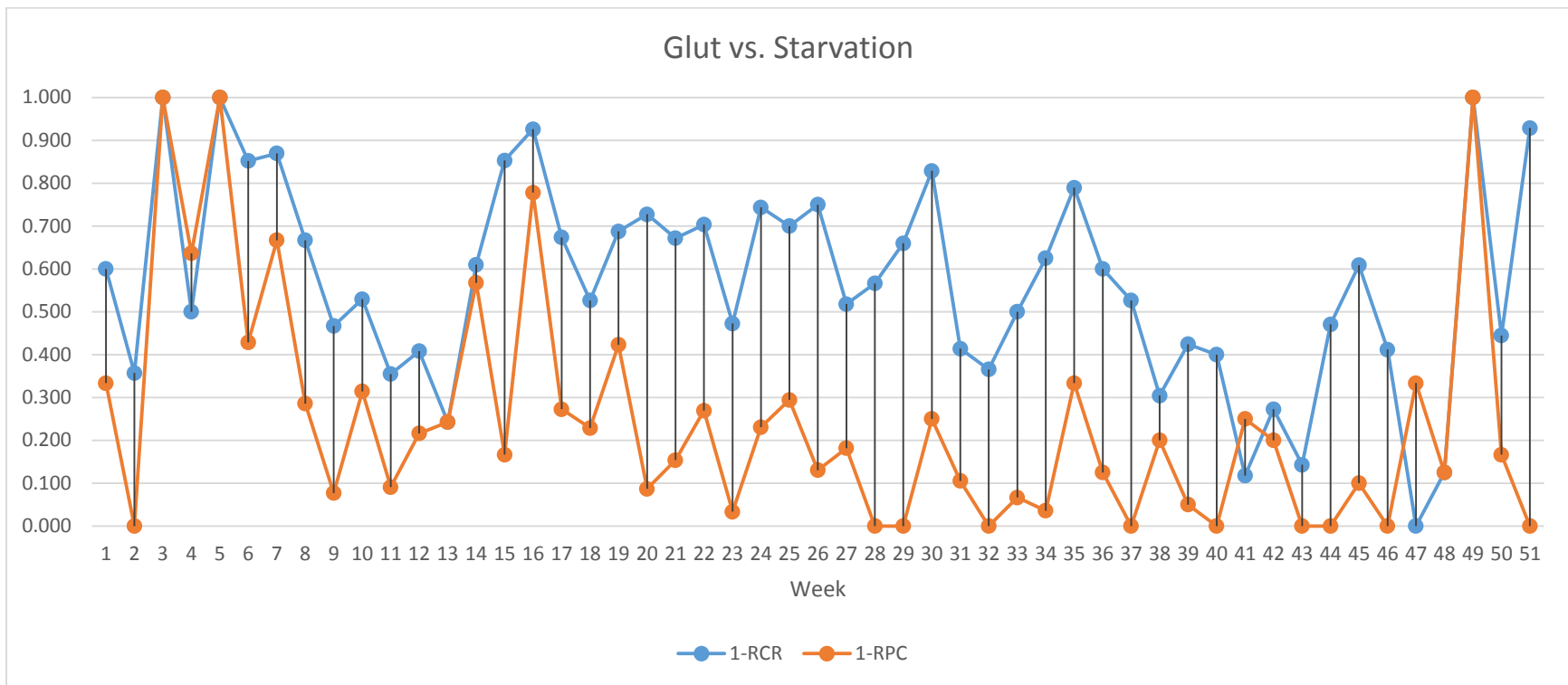


Figure 33 - P1T5: Glut vs. Starvation

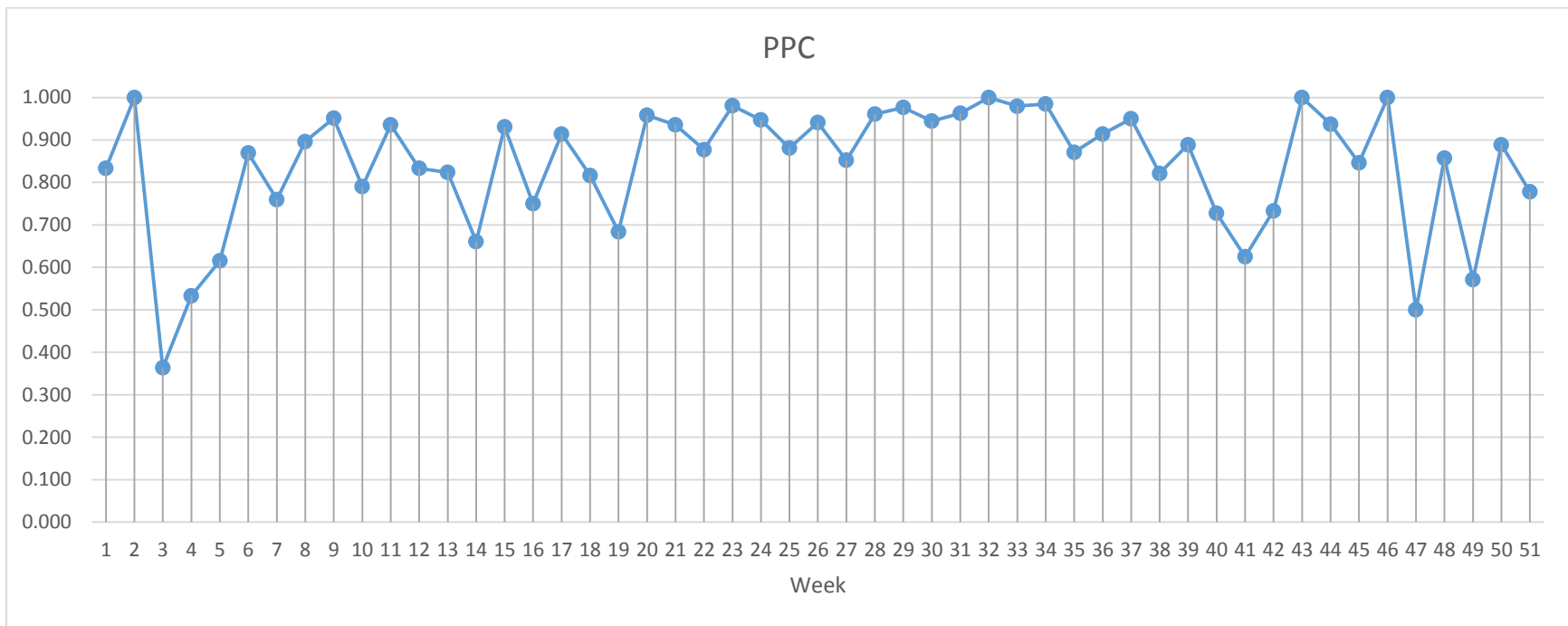


Figure 34 - P1T5: PPC

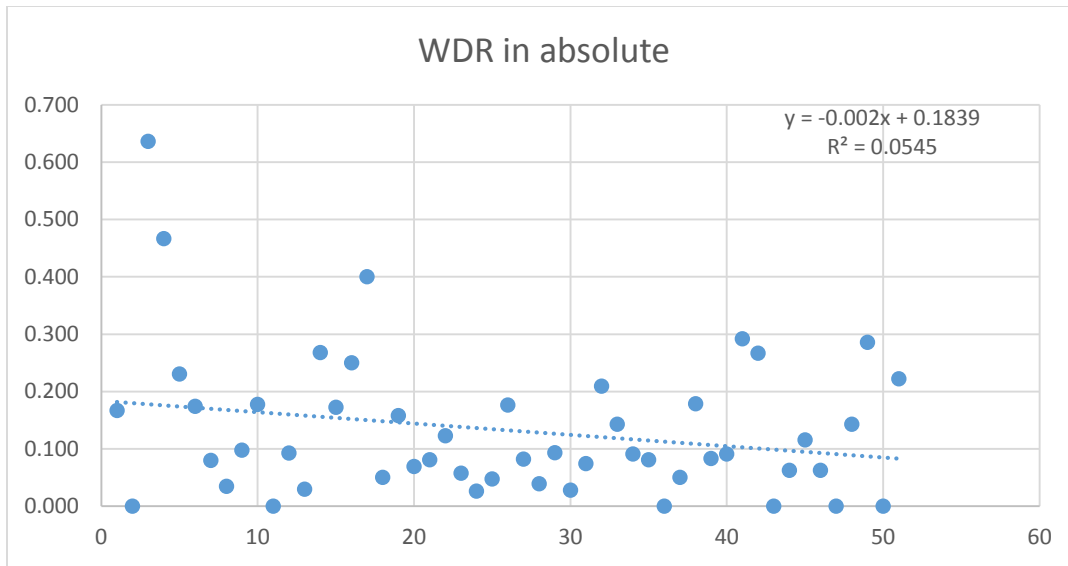


Figure 35 - P1T5: Time-Series Analysis of WDR in absolute

Table 13 - P1T5: Time-Series Regression and T-test Results

	Coefficients	Standard Error	t Stat	P-value
Intercept	0.184	0.035	5.233	0.000
Week	-0.002	0.001	-1.681	0.099

Team 7 (P1T7):

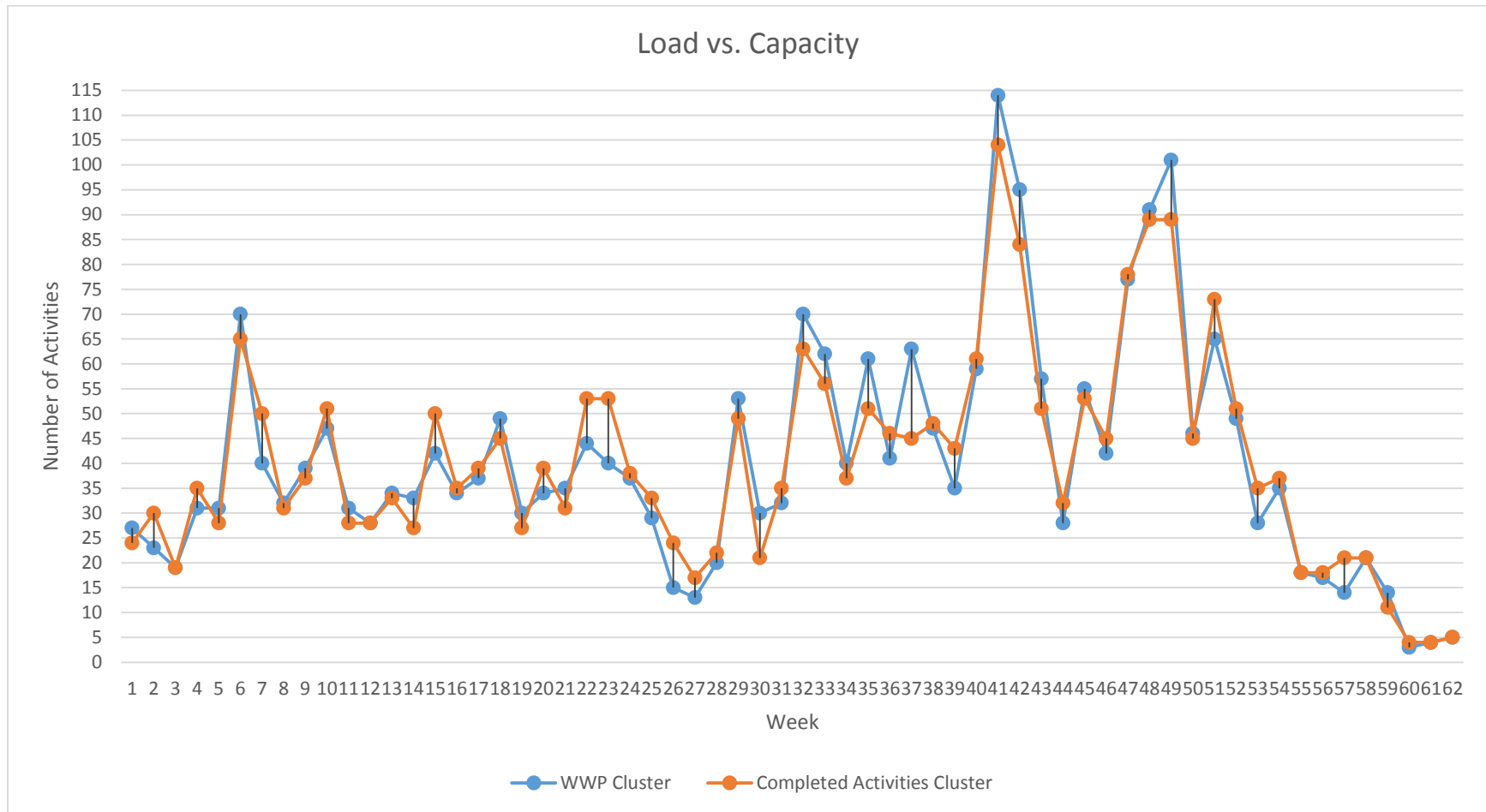


Figure 36 - P1T7: Load vs. Capacity

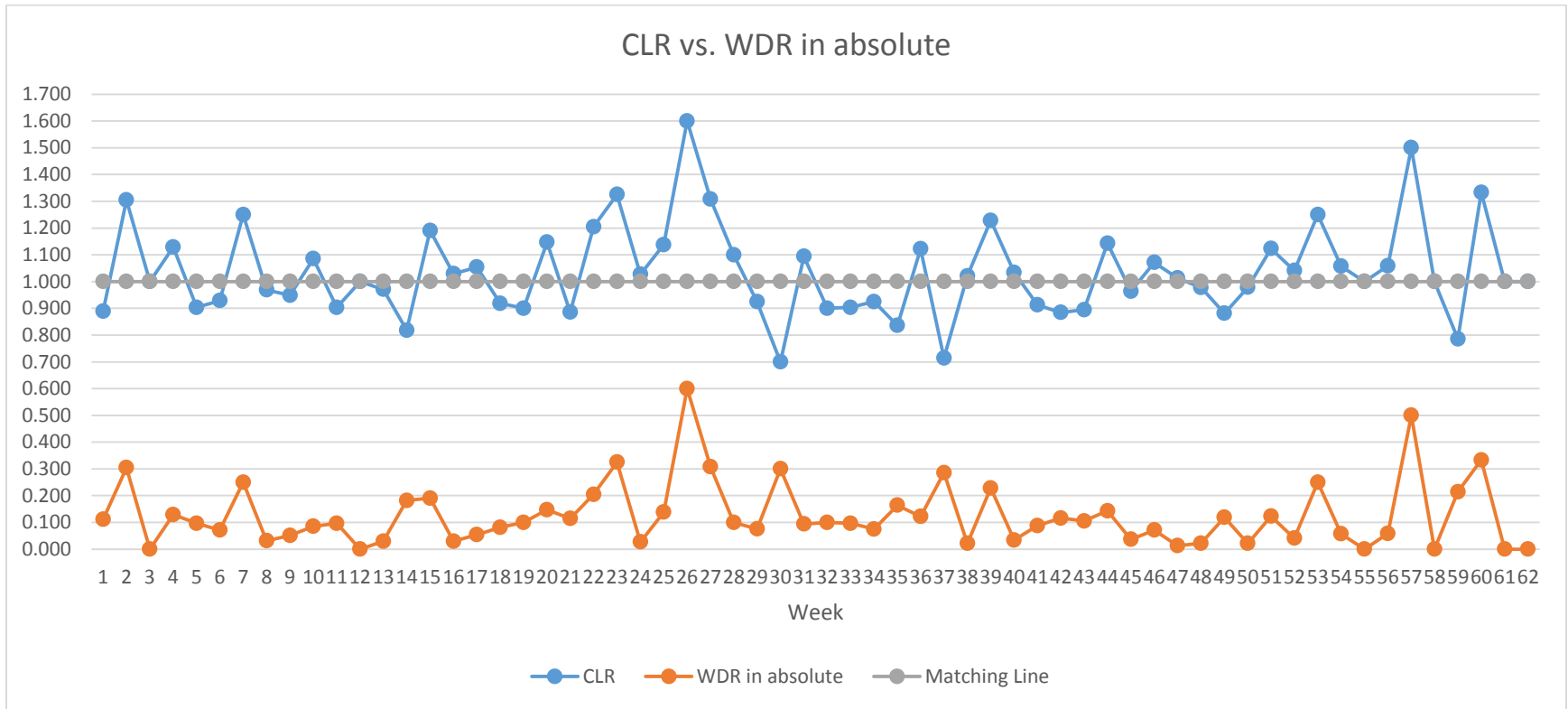


Figure 37 - P1T7: CLR vs. WDR in absolute

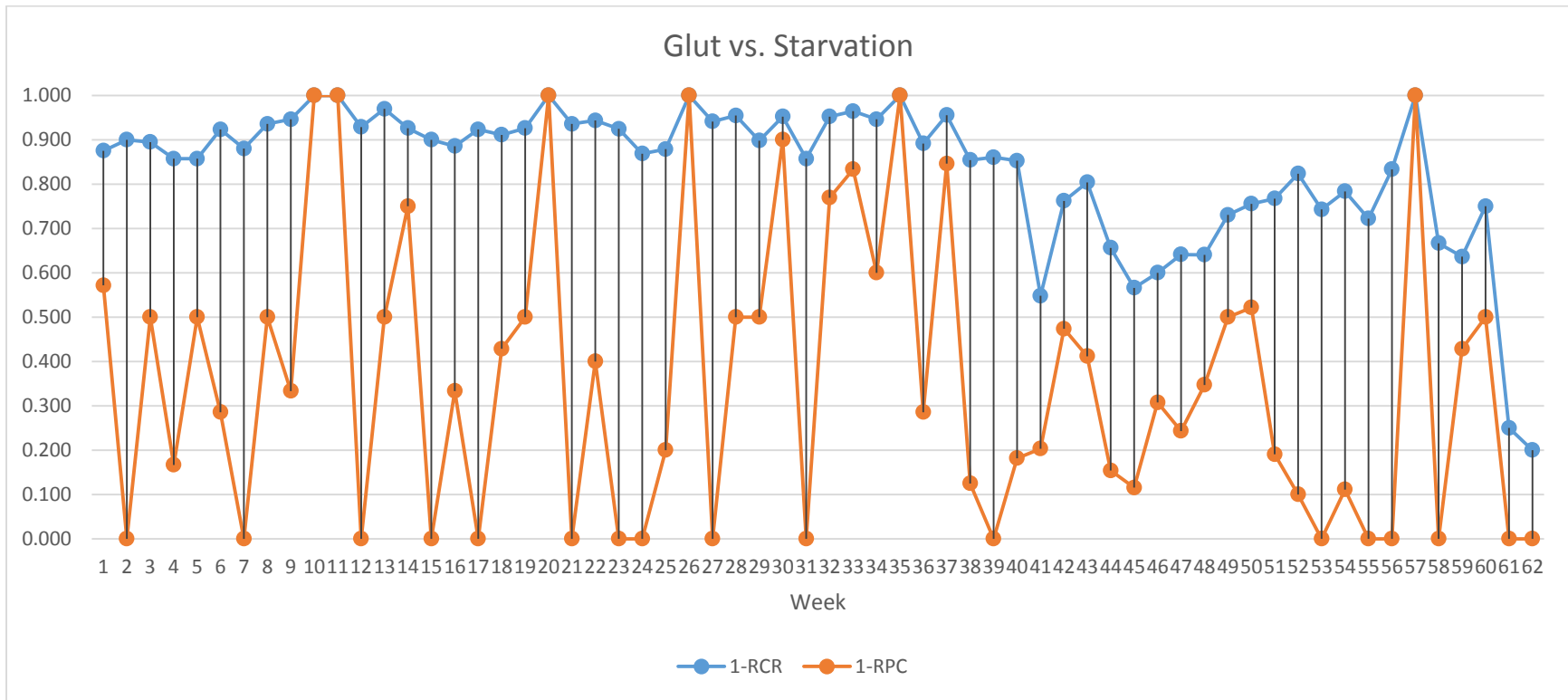


Figure 38 - P1T7: Glut vs. Starvation

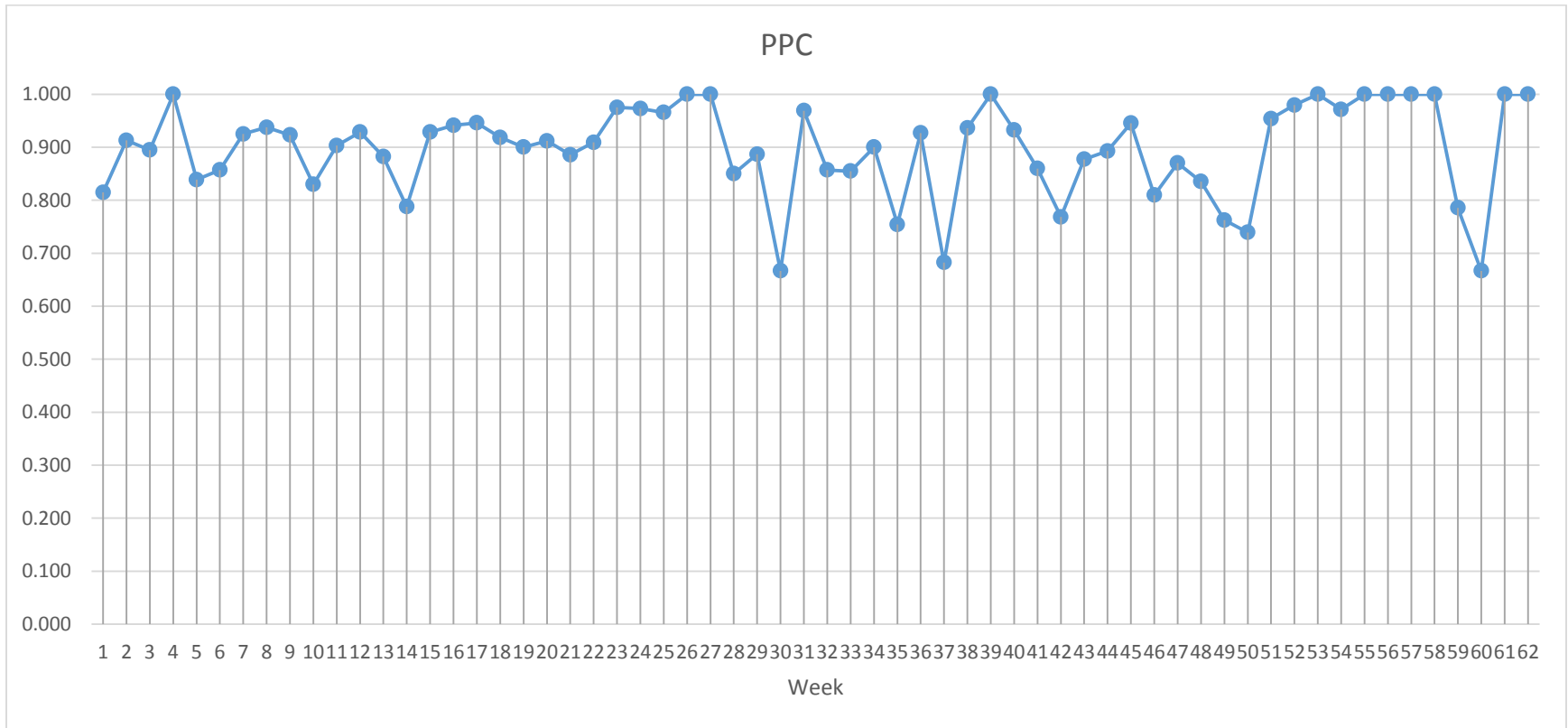


Figure 39 - P1T7: PPC

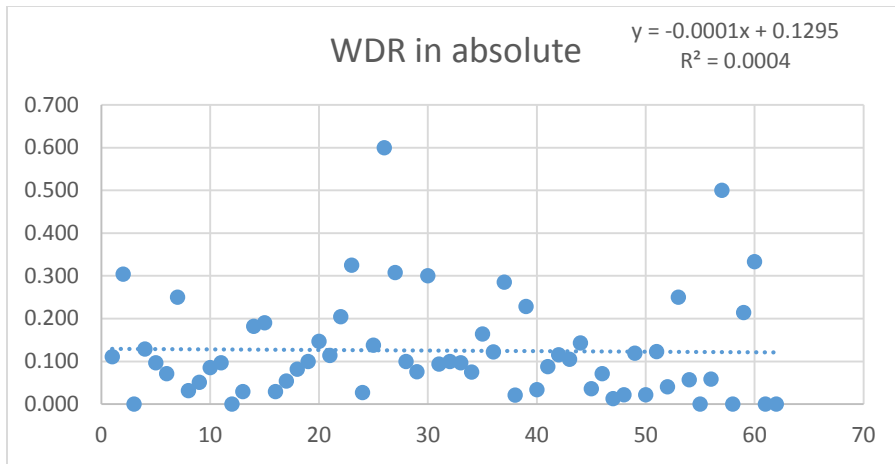


Figure 40 - P1T7: Time-Series Analysis of WDR in absolute

Table 14 - P1T7: Time-Series Regression and T-test Results

	Coefficients	Standard Error	t Stat	P-value
Intercept	0.130	0.031	4.167	0.000
Week	0.000	0.001	-0.158	0.875

Team 8 (P1T8):

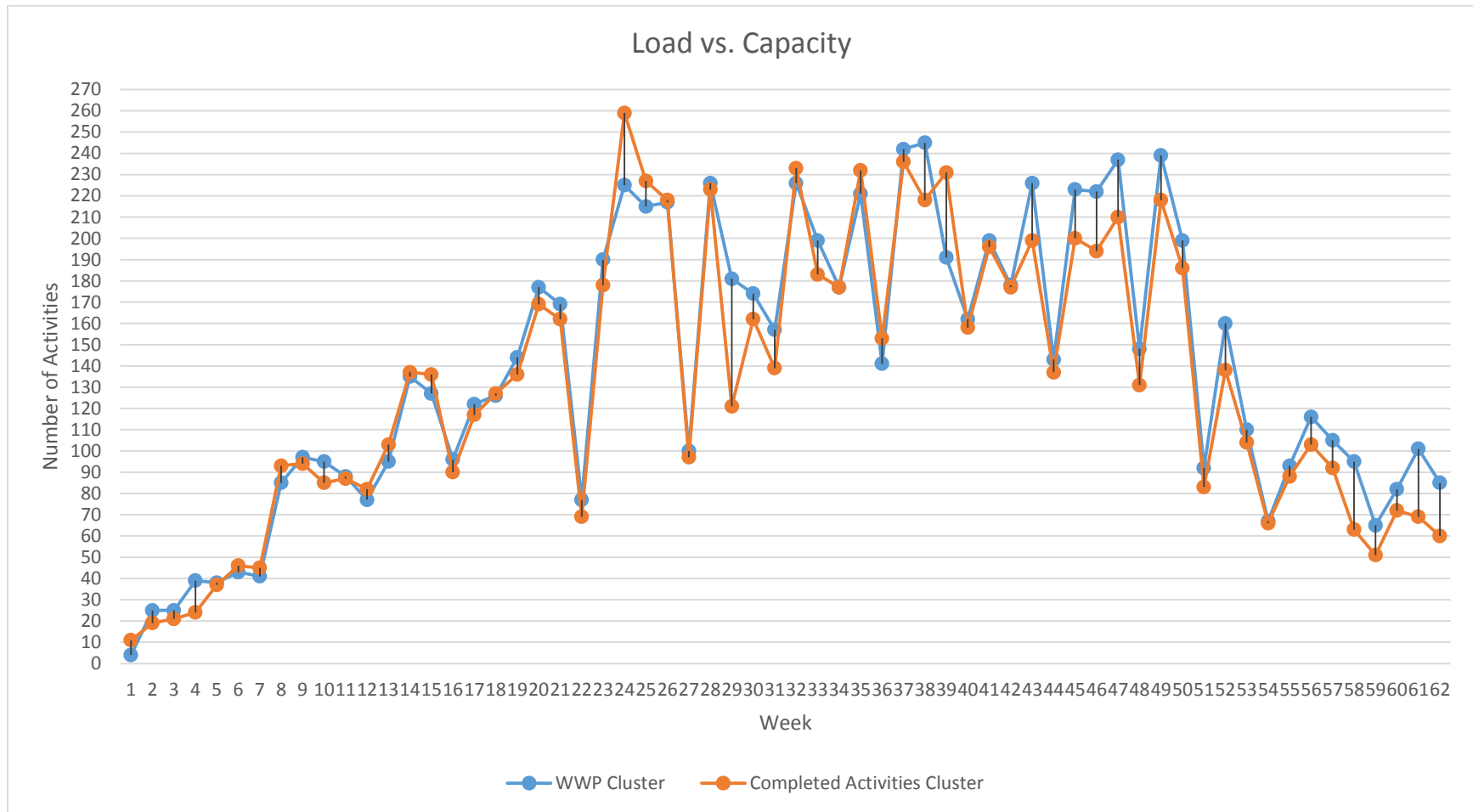


Figure 41 - P1T8: Load vs. Capacity

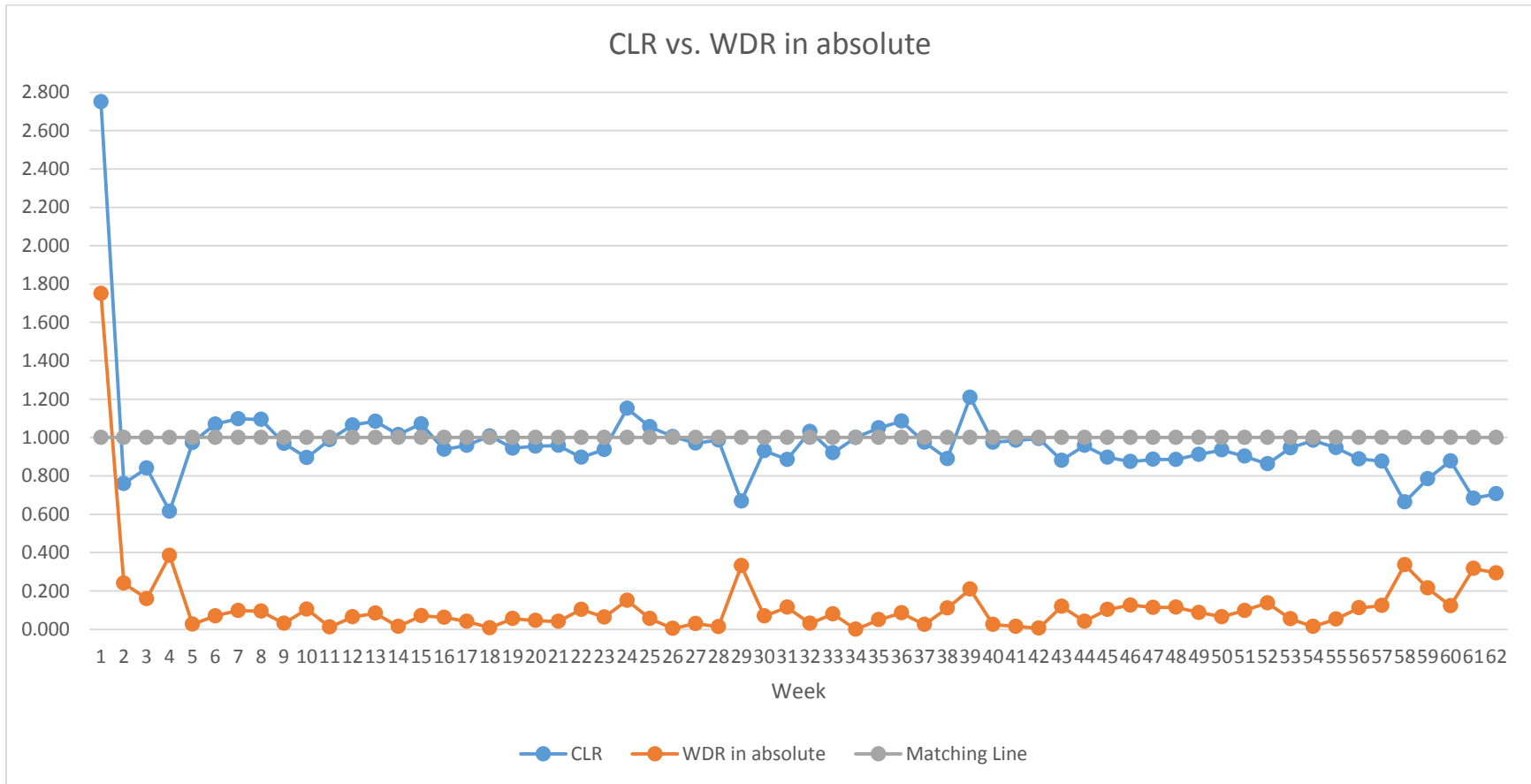


Figure 42 - PIT8: CLR vs. WDR in absolute

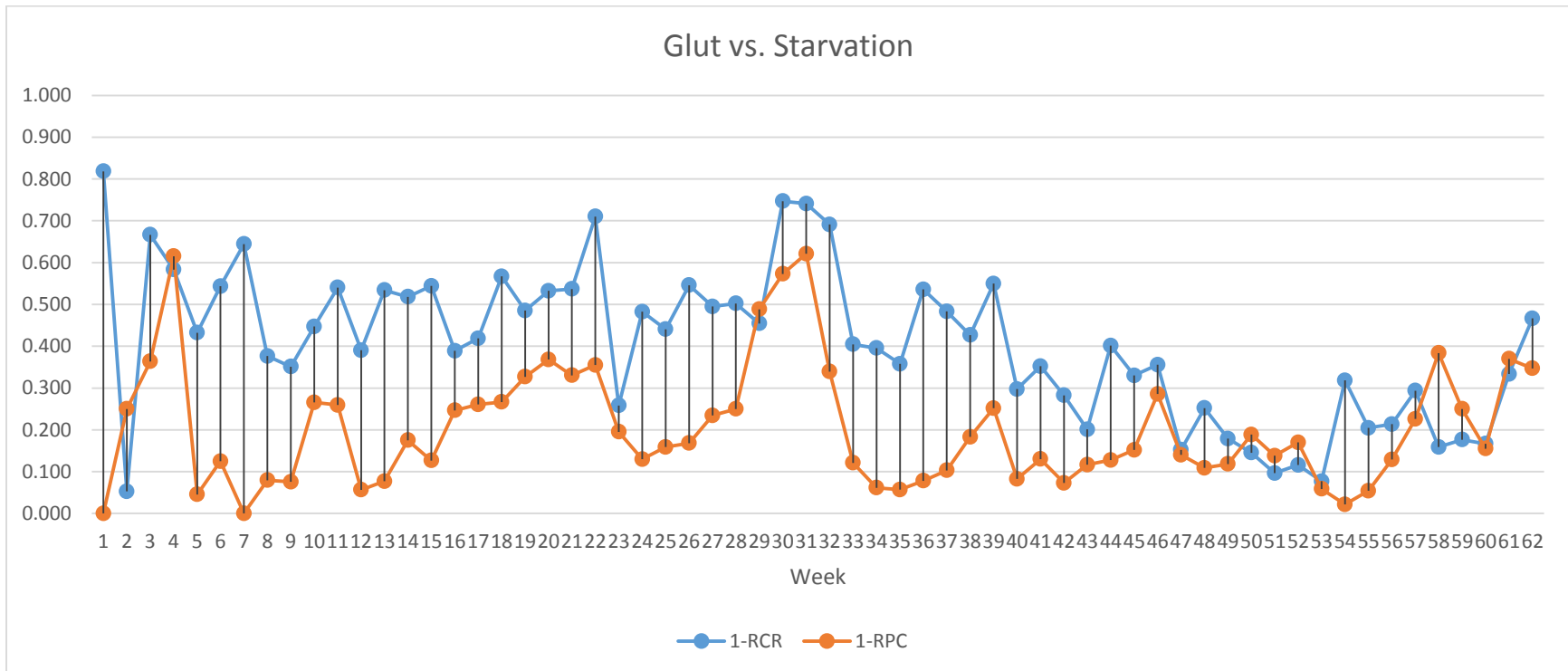


Figure 43 - P1T8: Glut vs. Starvation

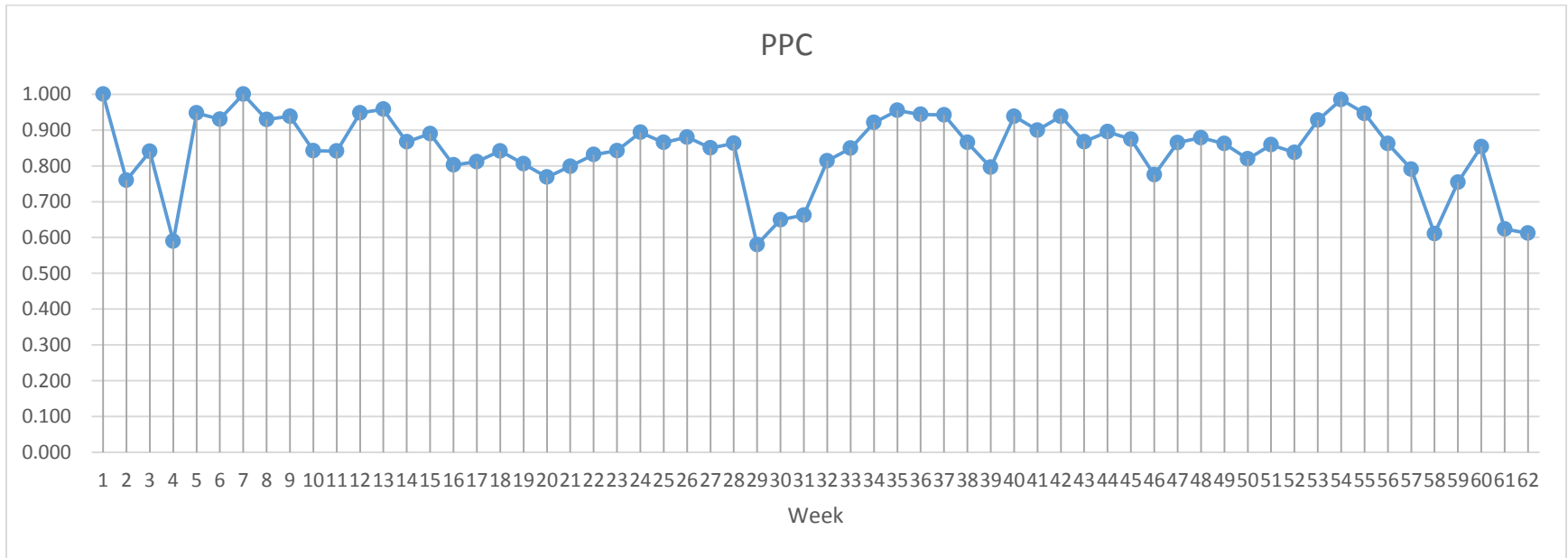


Figure 44 - PIT8: PPC

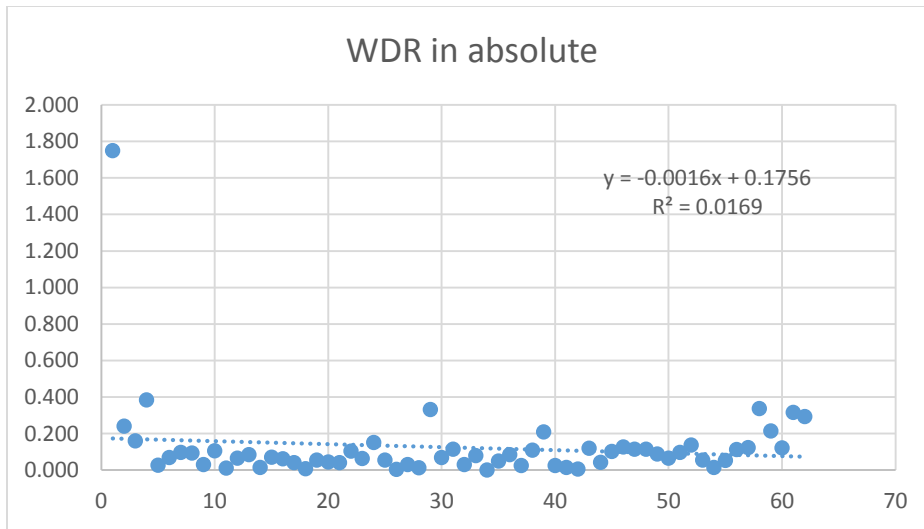


Figure 45 - P1T8: Time-Series Analysis of WDR in absolute

Table 15 - P1T8: Time-Series Regression and T-test Results

	Coefficients	Standard Error	t Stat	P-value
Intercept	0.176	0.058	3.003	0.004
Week	-0.002	0.002	-1.016	0.314

Team 9 (P1T9):

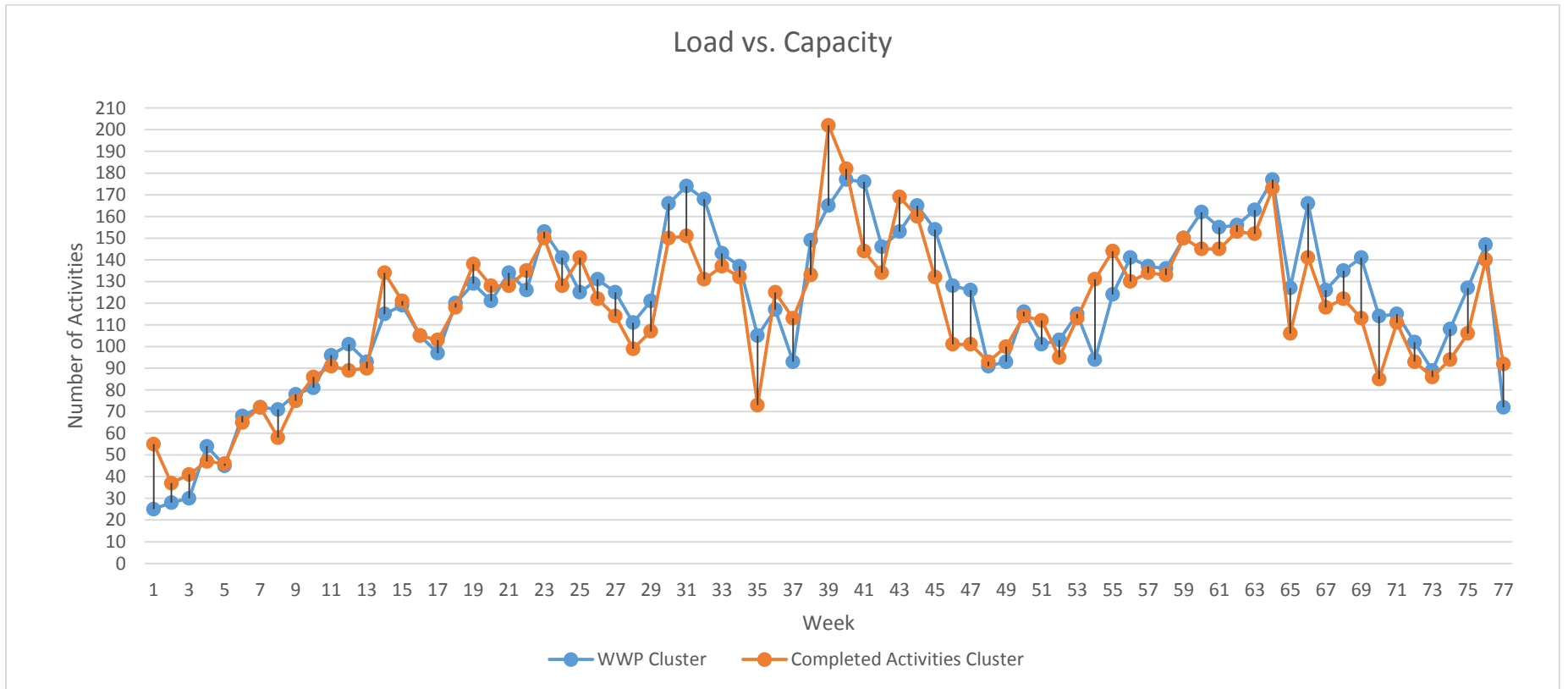


Figure 46 - P1T9: Load vs. Capacity

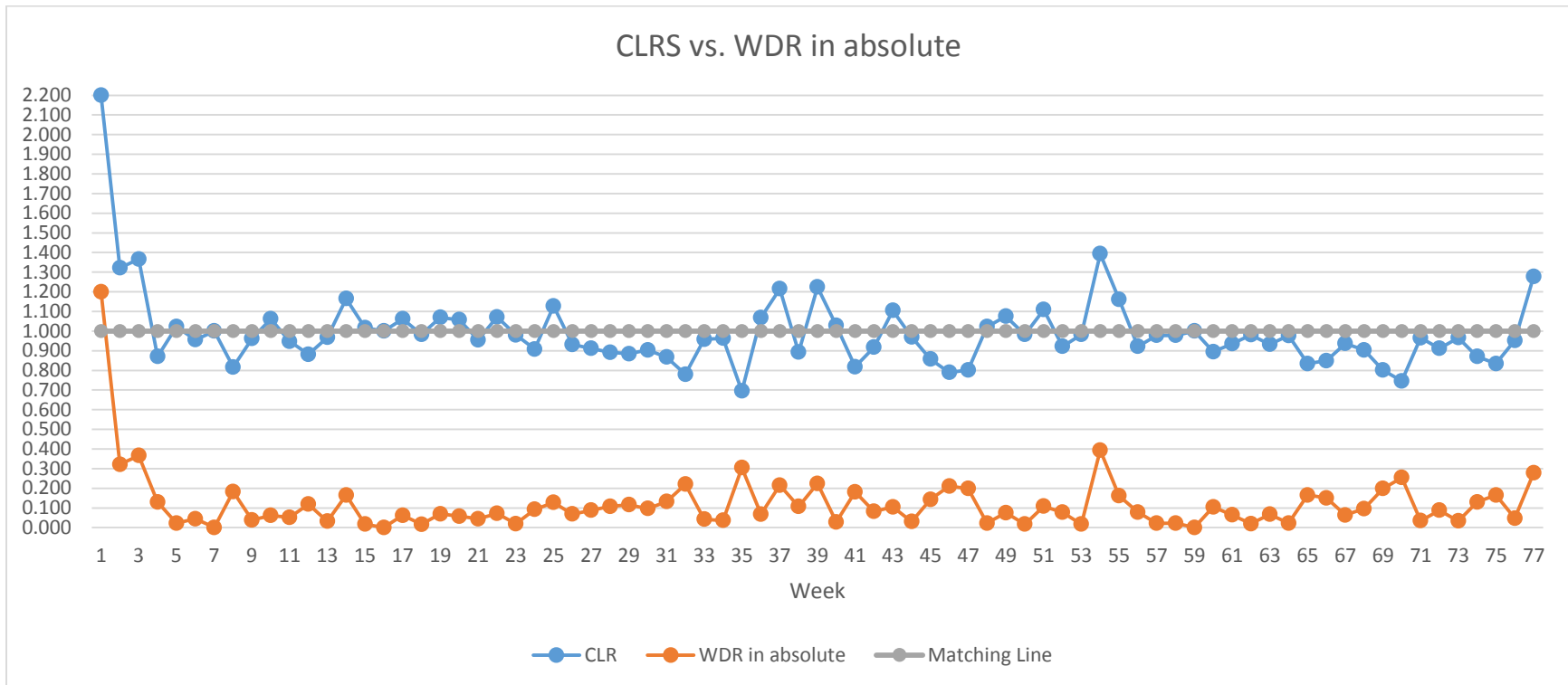


Figure 47 - P1T9: CLR vs. WDR in absolute

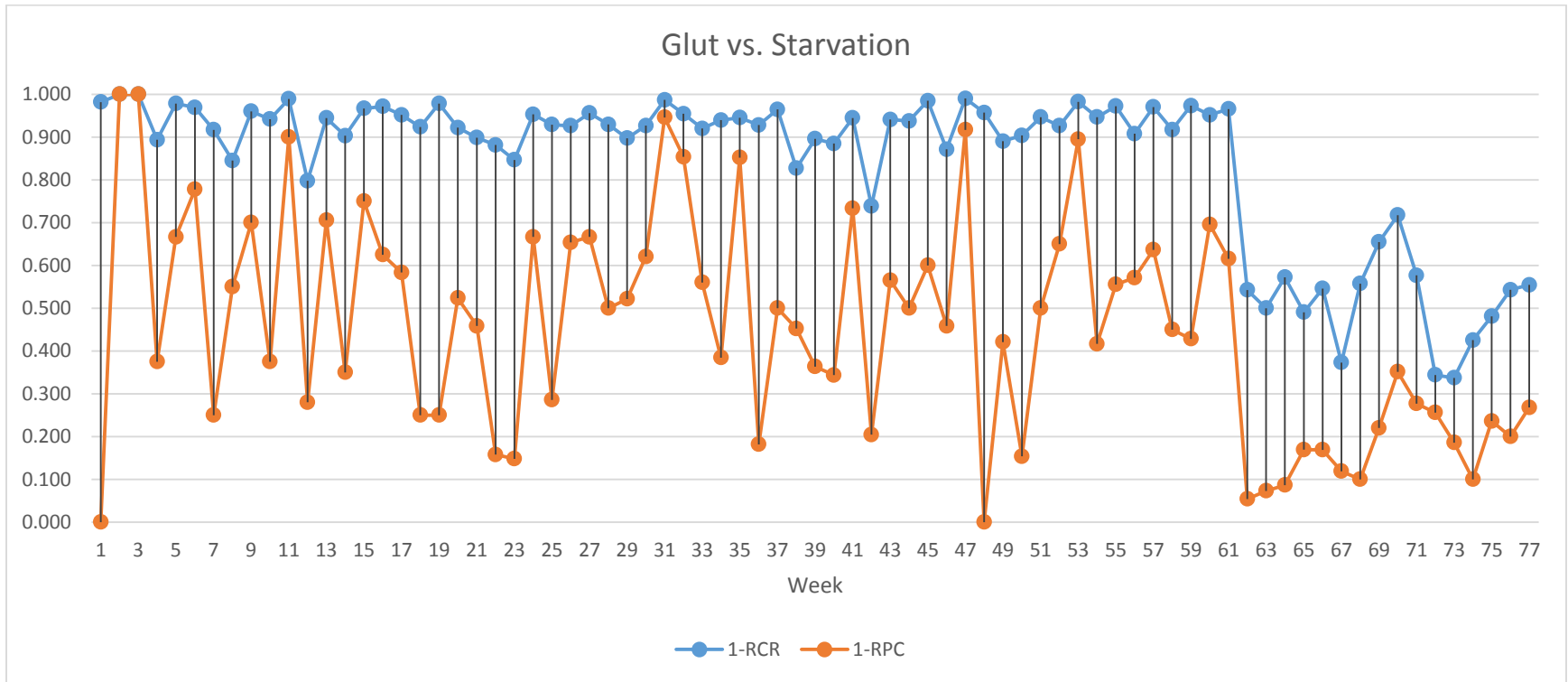


Figure 48 - P1T9: Glut vs. Starvation

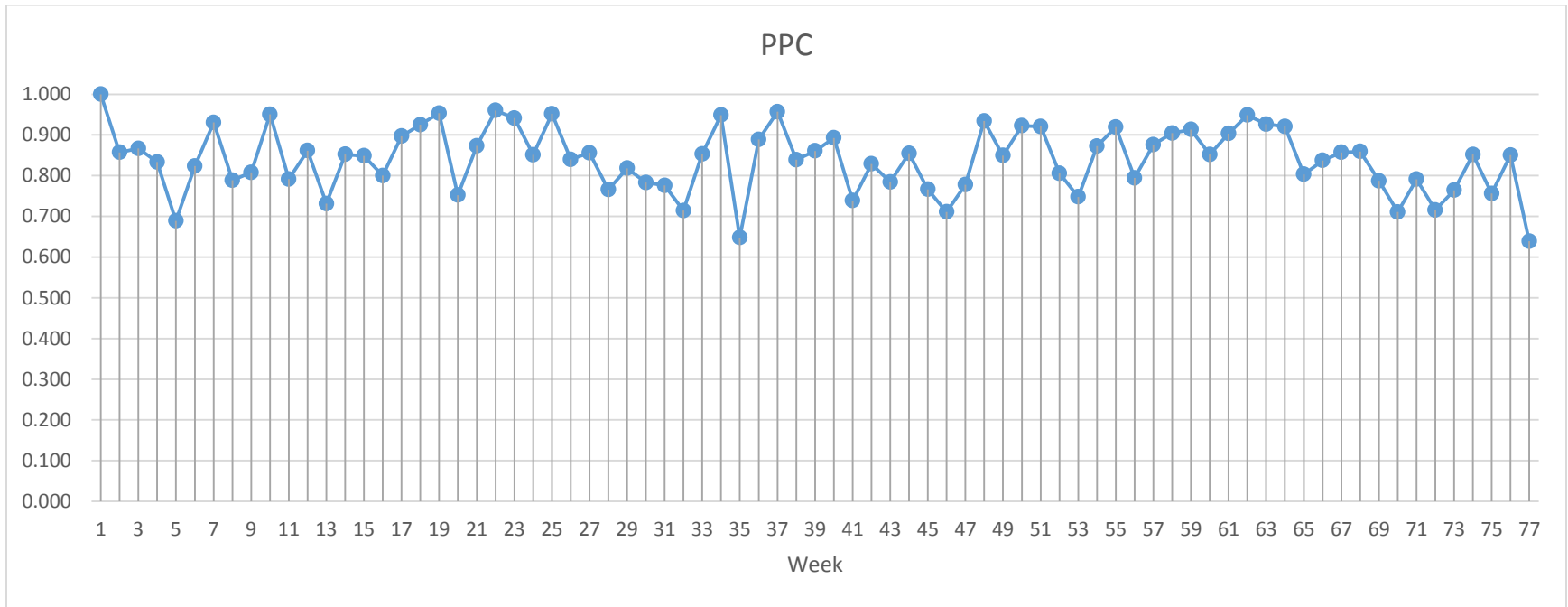


Figure 49 - P1T9: PPC

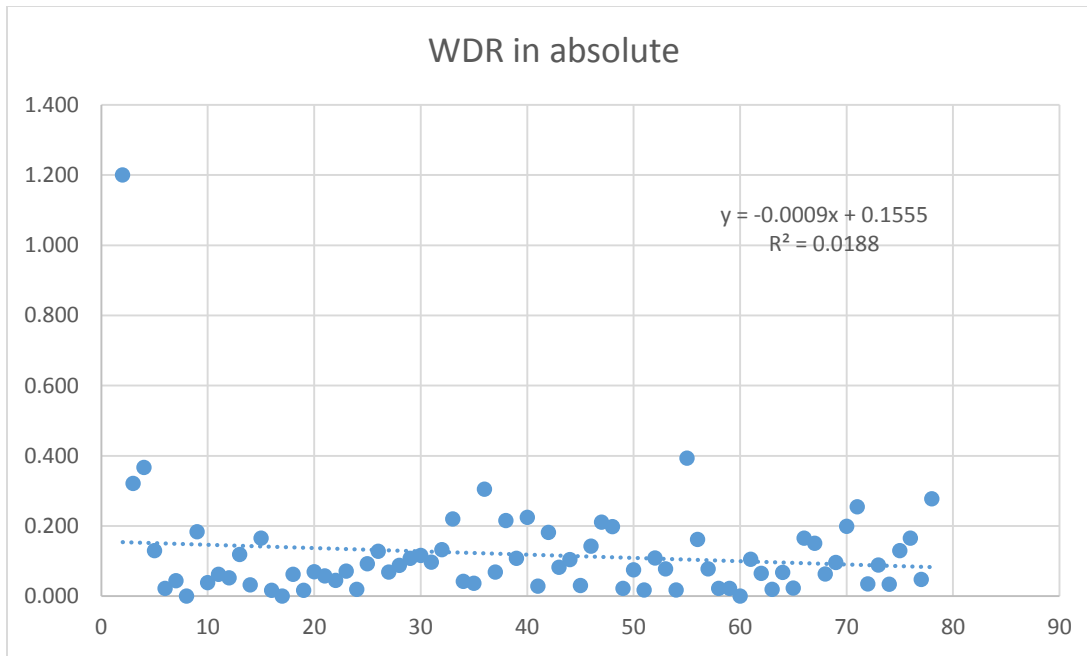


Figure 50 - P1T9: Time-Series Analysis of WDR in absolute

Table 16 - P1T9: Time-Series Regression and T-test Results

	Coefficients	Standard Error	t Stat	P-value
Intercept	0.156	0.036	4.365	0.000
Week	-0.001	0.001	-1.199	0.234

Project 2:

Team 1 (P2T1):

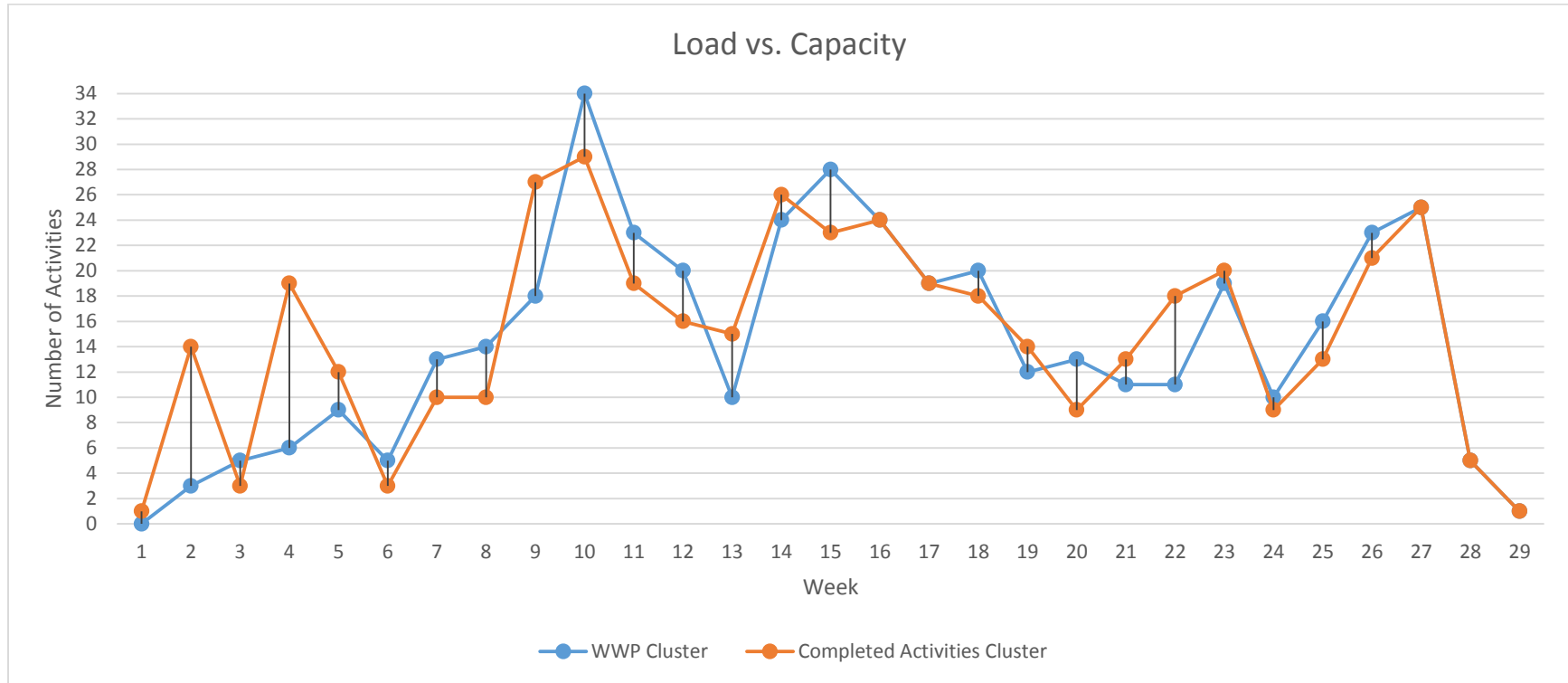


Figure 51 - P2T1: Load vs. Capacity

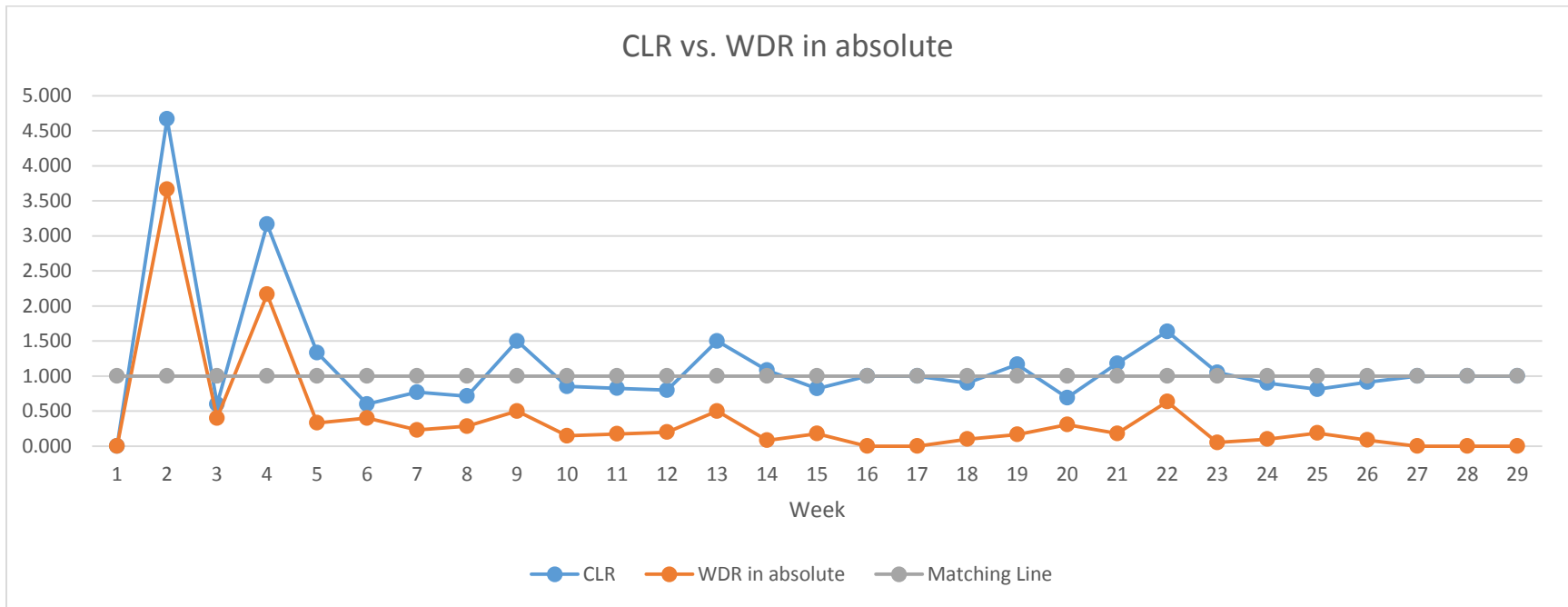


Figure 52 - P2T1: CLR vs. WDR in absolute

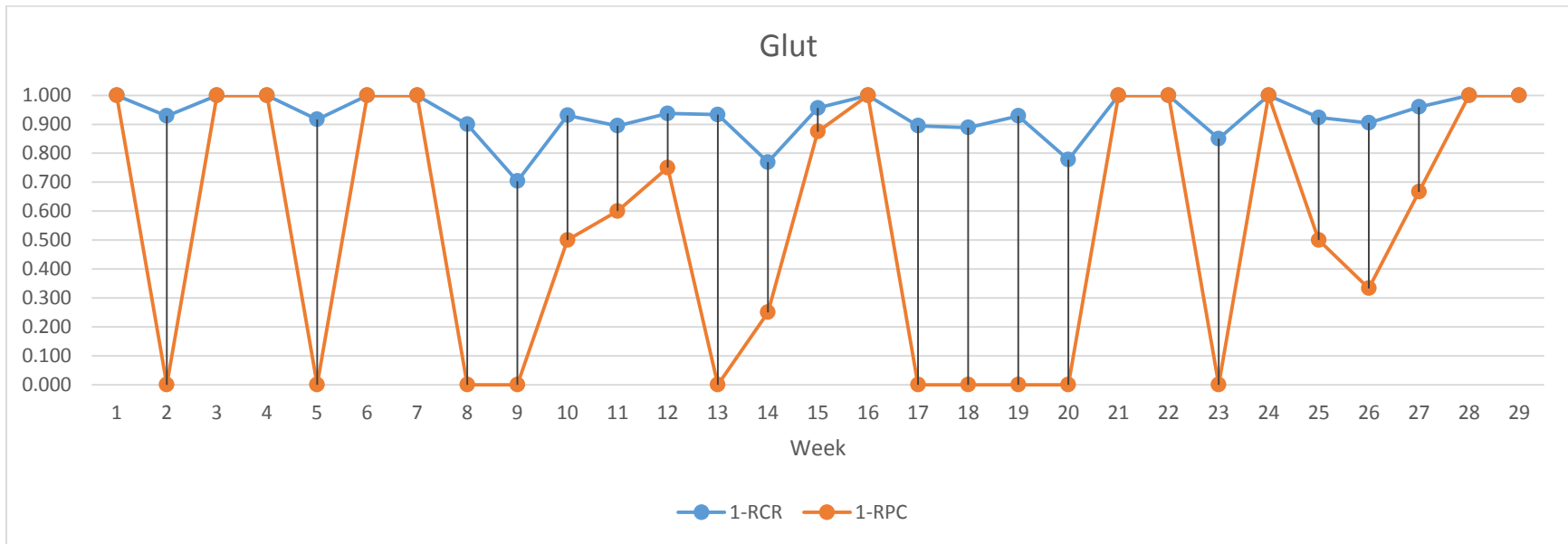


Figure 53 - P2T1: Glut vs. Starvation

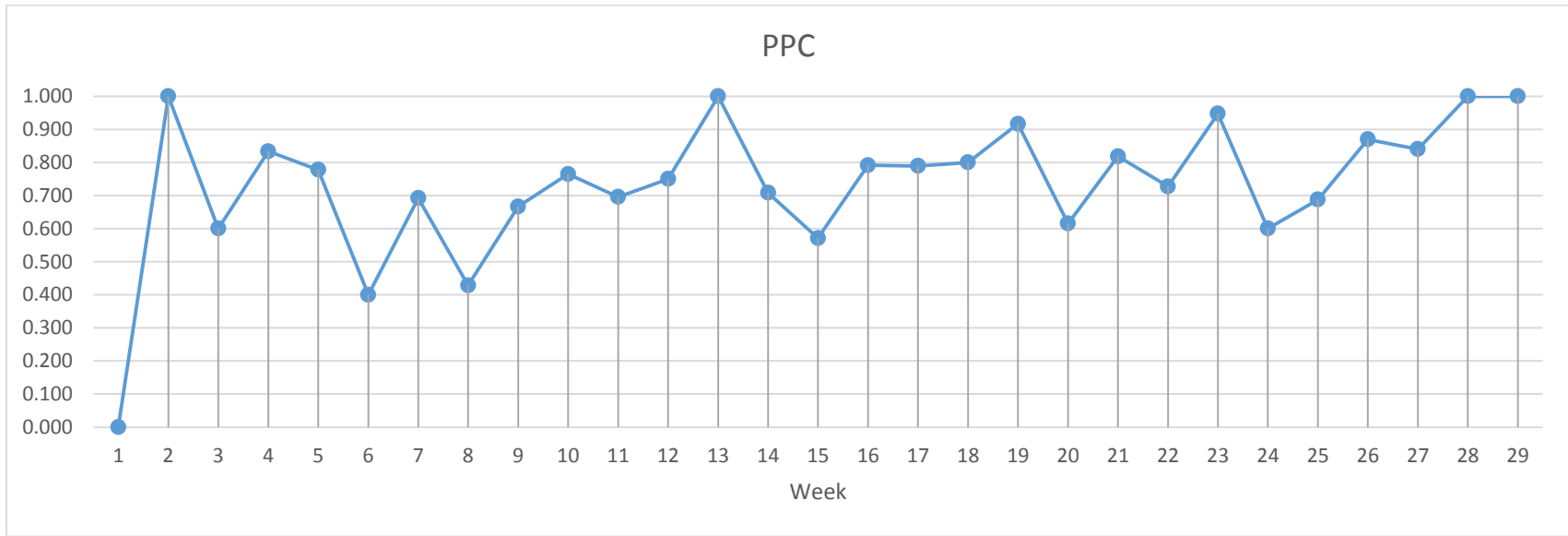


Figure 54 - P2T1: PPC

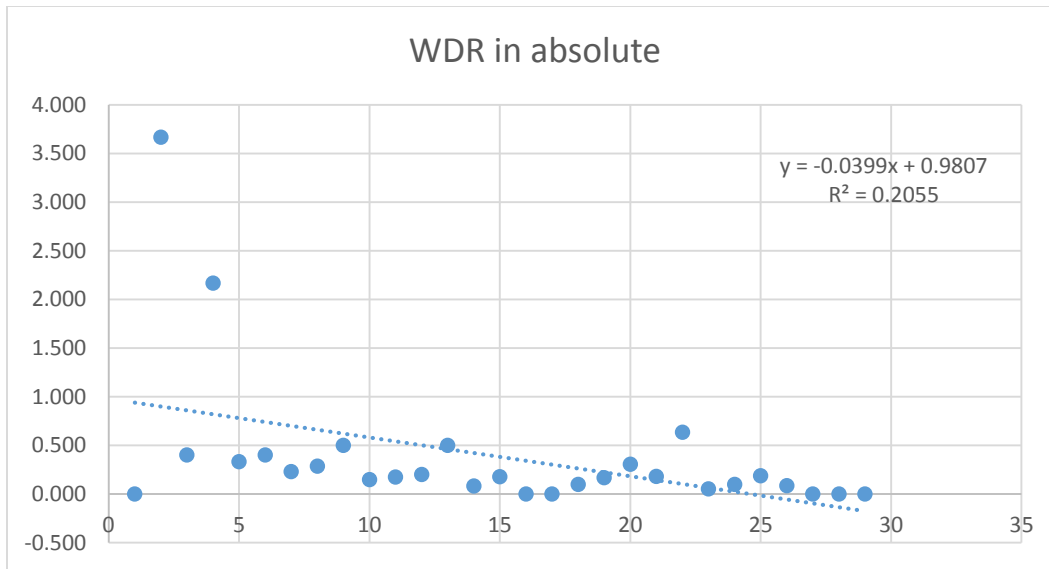


Figure 55 - P2T1: Time-Series Analysis of WDR in absolute

Table 17 - P2T1: Time-Series Regression and T-test Results

	Coefficients	Standard Error	t Stat	P-value
Intercept	0.981	0.259	3.782	0.001
Week	-0.040	0.015	-2.643	0.014

Team 3 (P2T3):

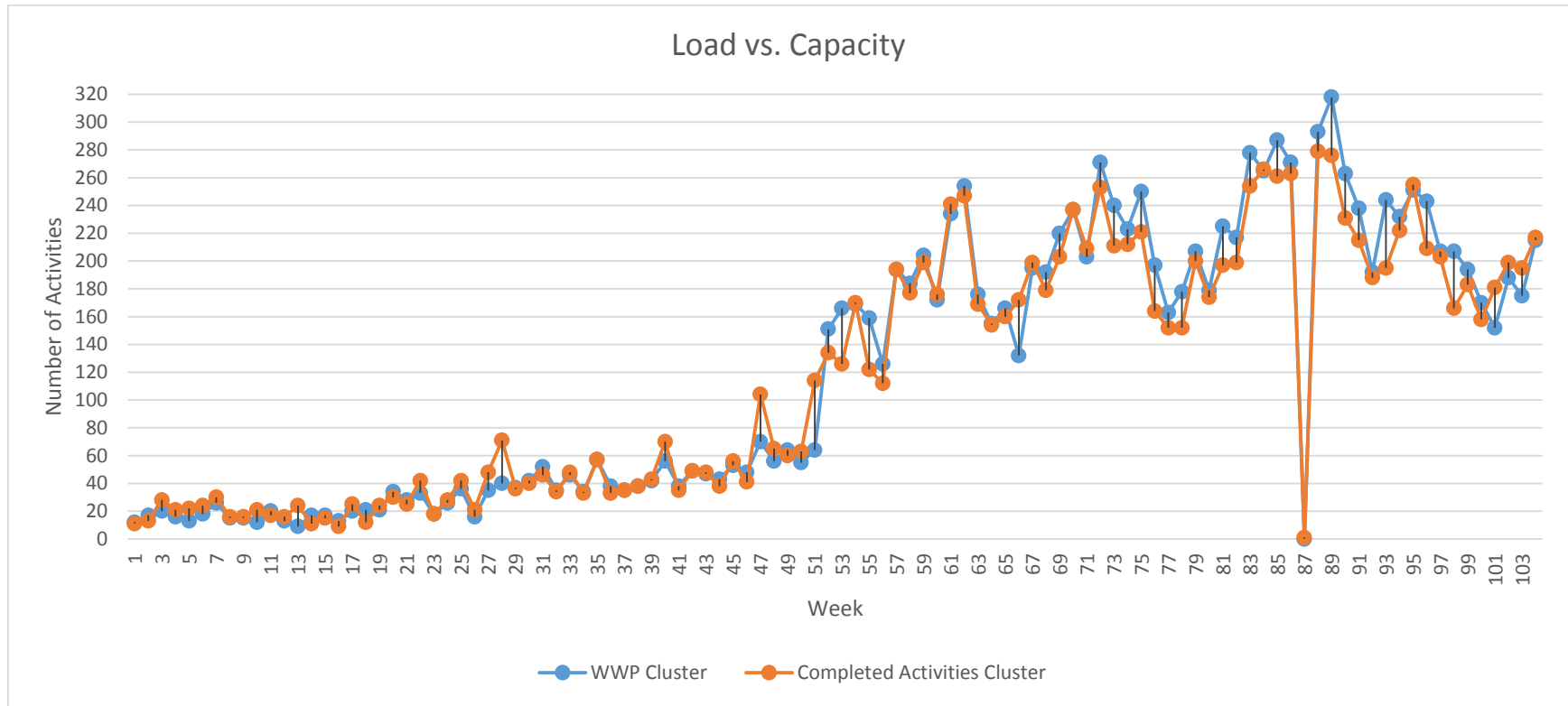


Figure 56 - P2T3: Load vs. Capacity

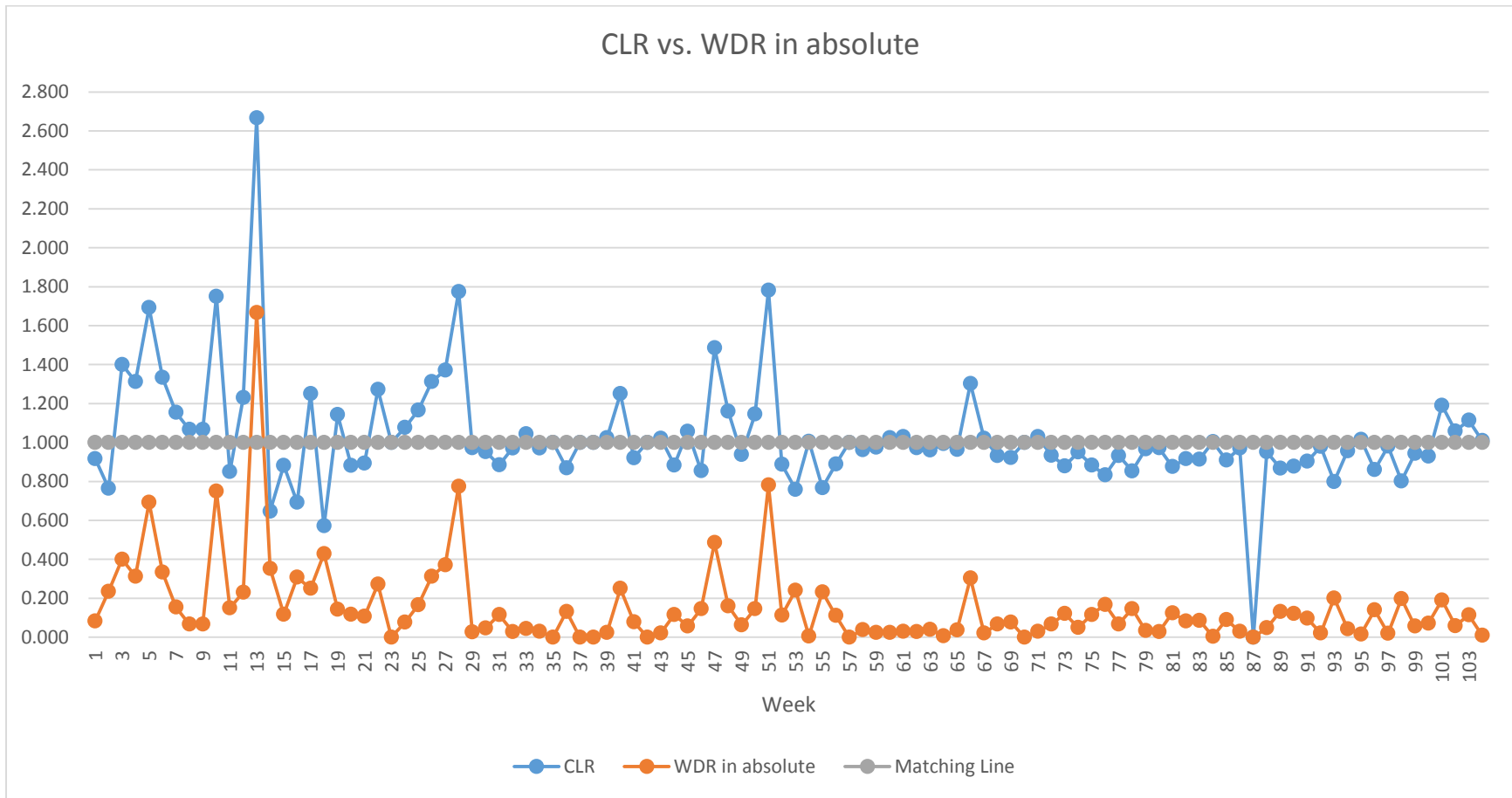


Figure 57 - P2T3: CLR vs. WDR in absolute

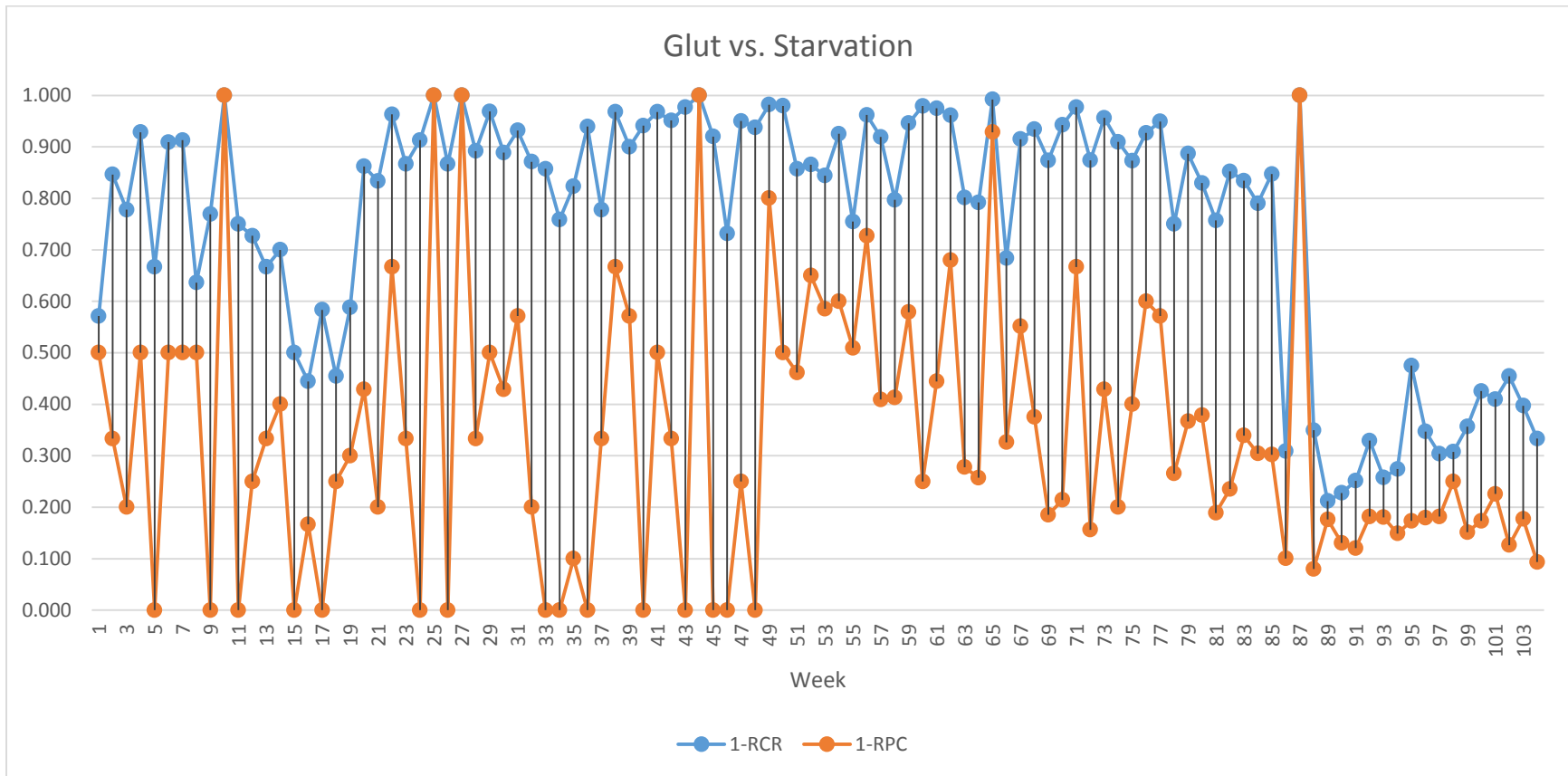


Figure 58 - P2T3: Glut vs. Starvation

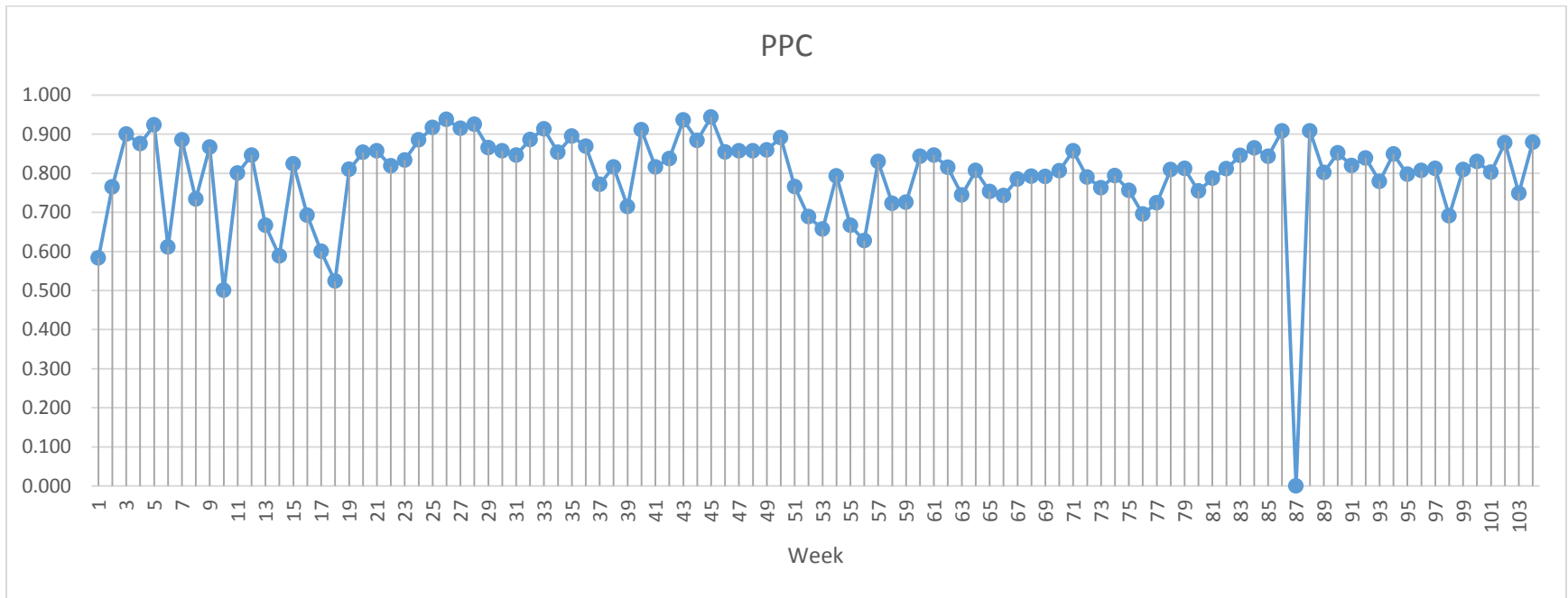


Figure 59 - P2T3: PPC

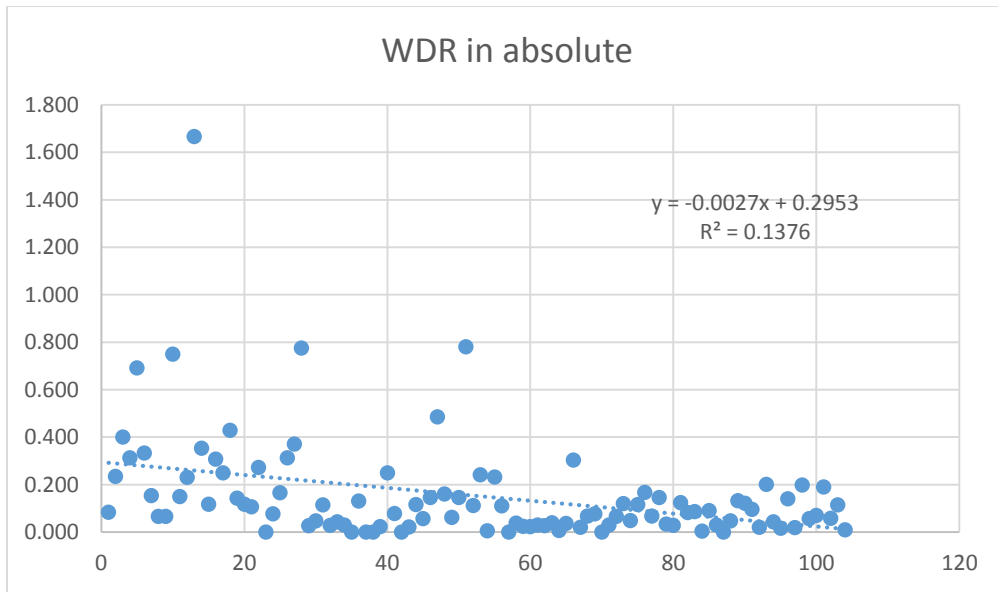


Figure 60 - P2T3: Time-Series Analysis of WDR in absolute

Table 18 - P2T3: Time-Series Regression and T-test Results

	Coefficients	Standard Error	t Stat	P-value
Intercept	0.295	0.041	7.246	0.000
Week	-0.003	0.001	-4.034	0.000

Team 4 (P2T4):

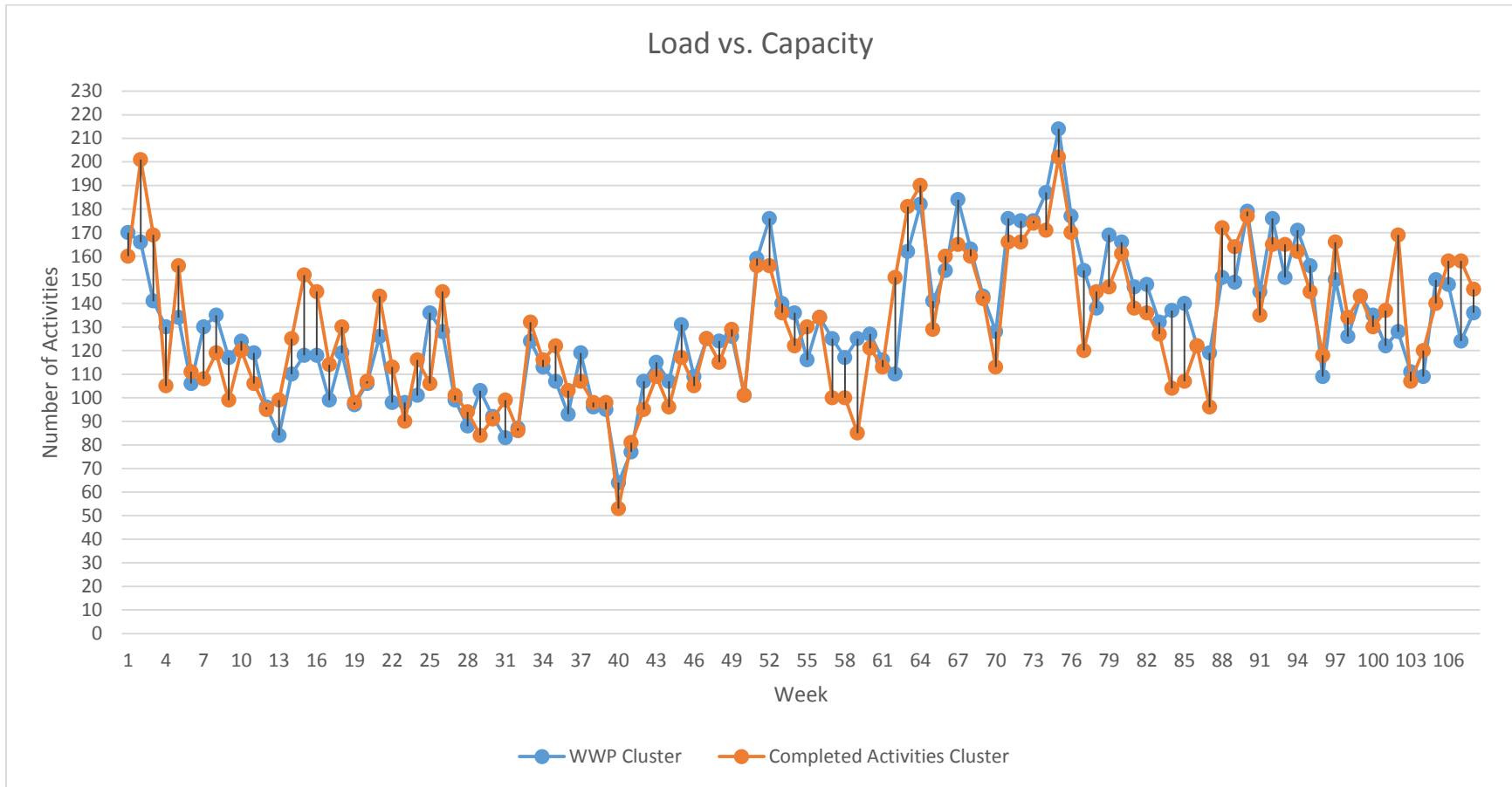


Figure 61 - P2T4: Load vs. Capacity

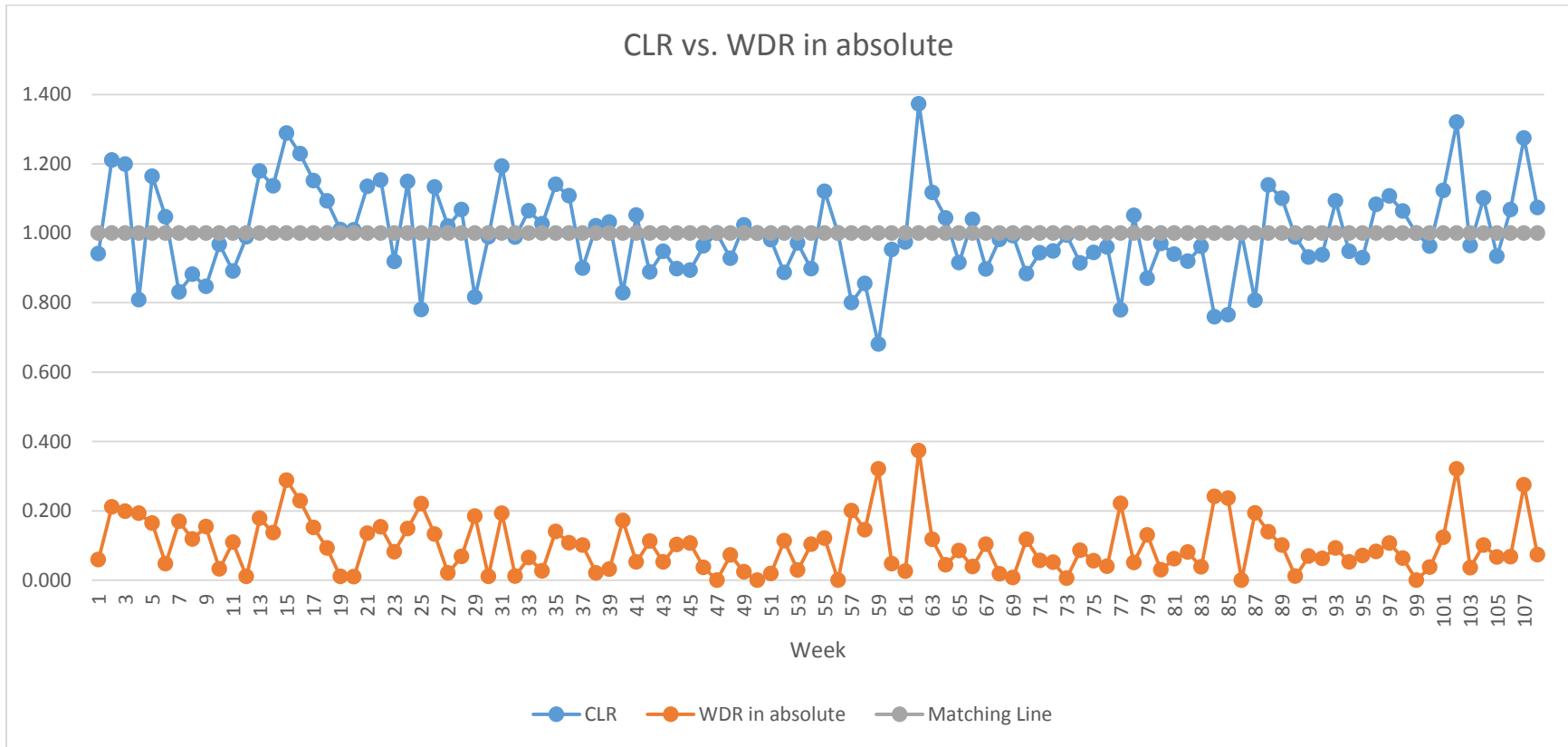


Figure 62 - P2T4: CLR vs. WDR in absolute

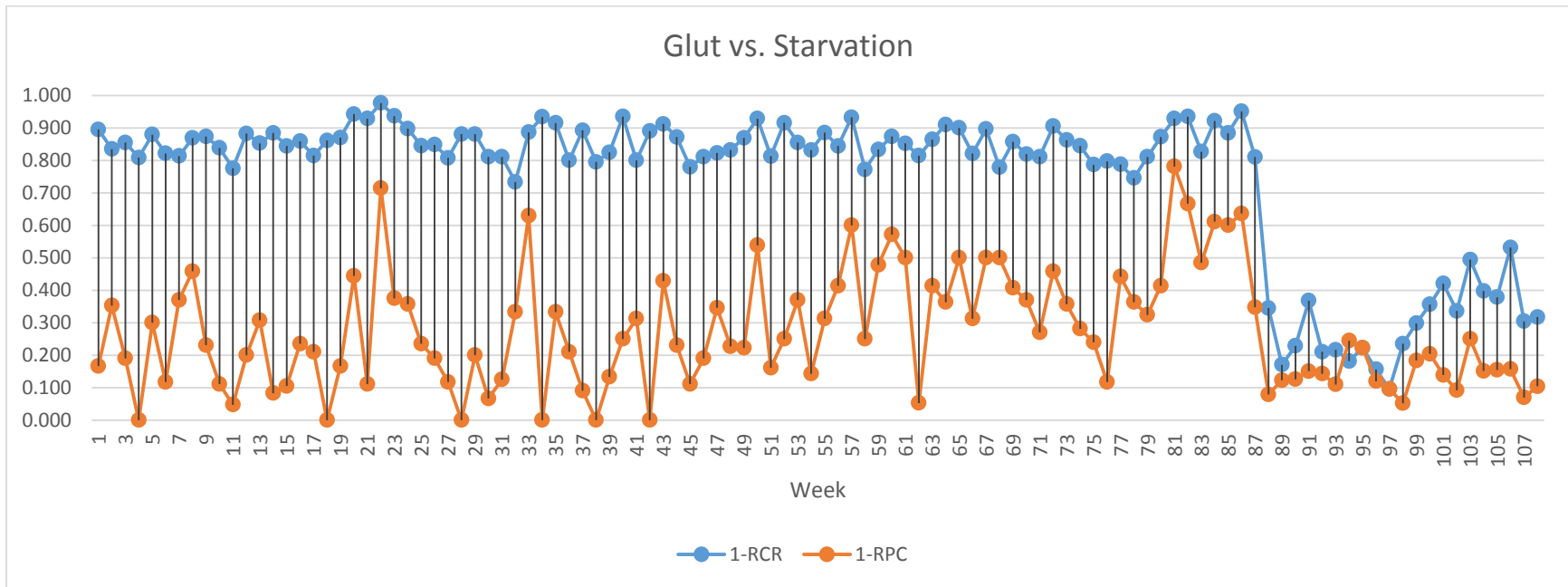


Figure 63 - P2T4: Glut vs. Starvation

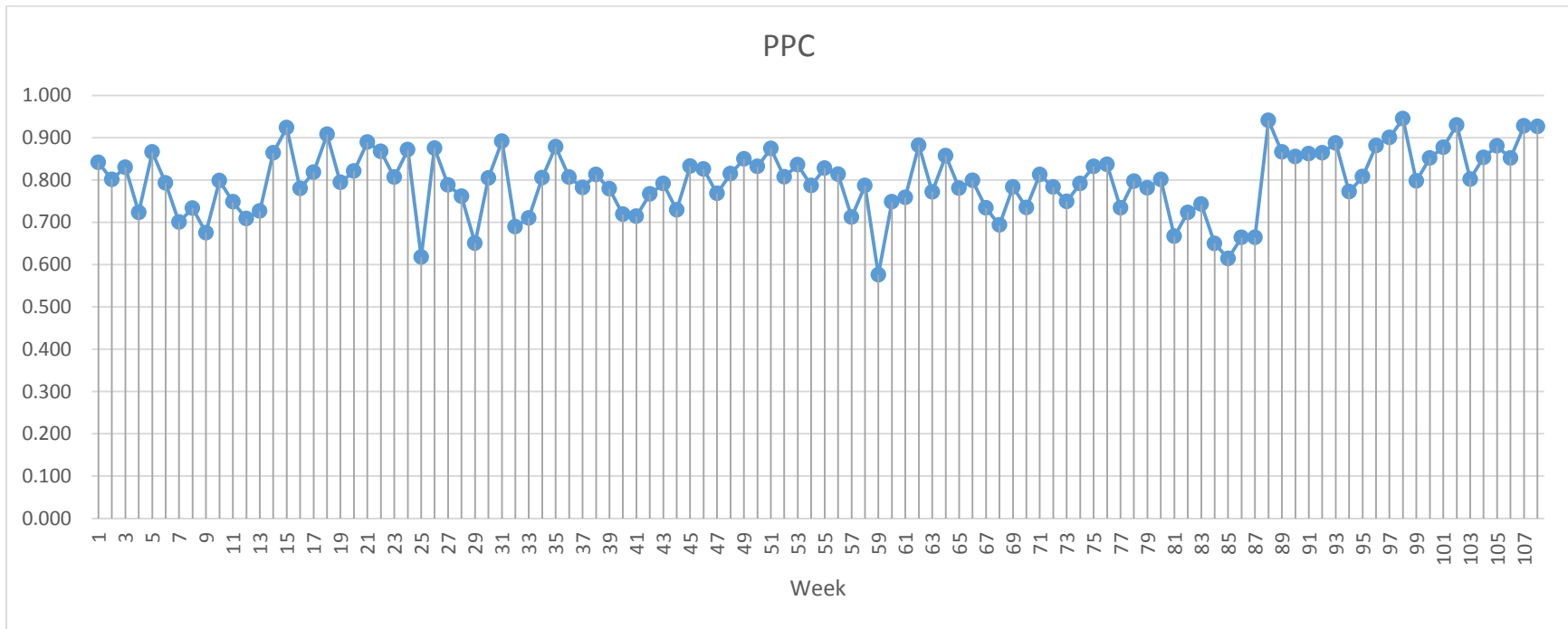


Figure 64 - P2T4: PPC

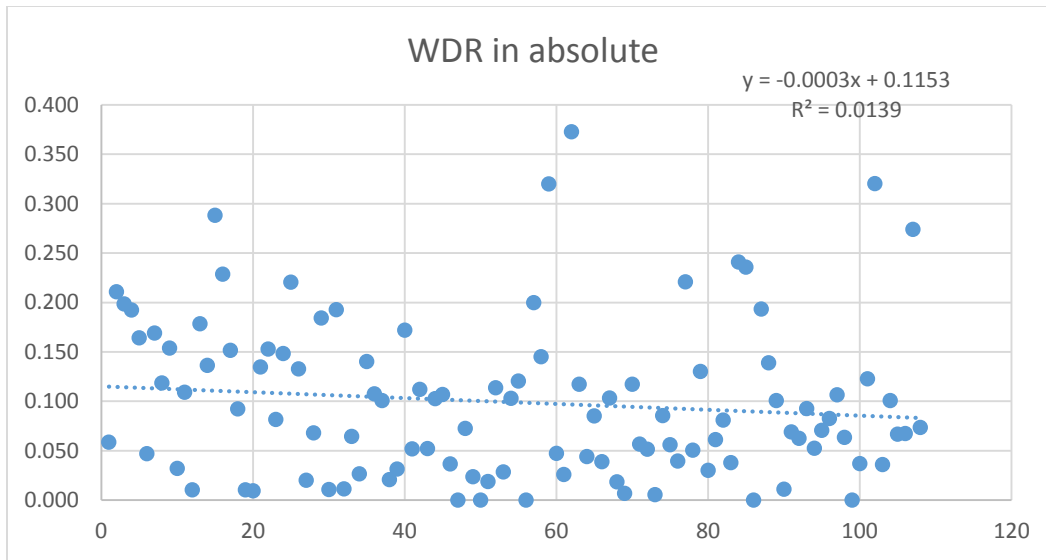


Figure 65 - P2T4: Time-Series Analysis of WDR in absolute

Table 19 - P2T4: Time-Series Regression and T-test Results

	Coefficients	Standard Error	t Stat	P-value
Intercept	0.115	0.015	7.538	0.000
Week	0.000	0.000	-1.221	0.225

