

Environmental Impact Analysis of Mechanical Systems and the Related Design Choices

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Abstract

Purpose - This study investigates the impact of a power budget constraint on the environmental impact of student-designed mechanical systems in the Mechanical Systems Design course at the University of Melbourne. The study aims to determine the effect on student built mechanical designs of limiting steady-state power consumption to 2.5W.

Hypothesis - The introduction of a power budget would incentivise students to develop lighter-weight projects, as such systems inherently require less energy to maintain steady-state motion. Consequently, it was expected that Semester 2 projects would demonstrate lower environmental impact scores, particularly for moving components and materials, and that such results would be statistically significantly different to semester 1.

Study Design - A comparative analysis was conducted across two semesters: Semester 1, where students designed without power budgets, and Semester 2, where a 2.5W steady-state power budget was introduced. Environmental impact metrics were evaluated using a weight-based Life Cycle Assessment approach, and statistical analyses, including the Mann-Whitney U test and independent t-tests, were used to assess differences in material and component environmental impact distributions.

Findings - Contrary to expectations, no statistically significant difference in total environmental impact was observed between semesters, indicating that projects may have already been sufficiently lightweight to operate within the imposed power budget. Instead of reducing environmental, the constraint influenced design trade-offs, shifting material selection. These findings highlight the role of constraints in shaping student decision making in engineering education, offering insights for future curriculum development and sustainability focused interventions.

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Nomenclature

S_{Total} - Total EI of Static Materials/Components per semester.

S_{Avg} - Average EI per project of Static Materials/Components per semester.

S1 Rank - Mean rank of semester 1 data points

S2 Rank - Mean rank of semester 2 data points

U_{S1} - U statistic for semester 1 data points.

U_{S2} - U statistic for semester 2 data points.

z - Standardized Test Statistic.

p - P-value of the Test

H_0 - Null Hypothesis

Mean $\pm$ *SD* - Mean value $\pm$ Standard Deviation.

Δ - Difference between means (Semester 2 - Semester 1).

95% CI - 95% Confidence Interval for the difference between means.

$t(df)$ - t-statistic with degrees of freedom (df).

MDF - Medium-Density Fibreboard.

Conn. - Connector

1 Introduction

The increasing urgency to address environmental challenges has led to a growing recognition of the need for sustainable practices in engineering education. International frameworks, such as the United Nations Sustainable Development Goals (SDGs), emphasise the role of engineering in creating sustainable solutions. However, efforts to incorporate sustainability into higher education programs often fall short, with limited emphasis on practical tools that bridge theoretical concepts and real-world applications. Project-Based Learning has emerged as a critical pedagogical tool for integrating sustainability into engineering education, providing students with practical design experience while reinforcing sustainability principles. However, the absence of systematic assessment in existing project-based interventions raises concerns about whether students actively optimise for sustainability or merely conform to project requirements without deeper engagement.

This study introduces the concept of a power budget, a novel intervention embedded within the project requirements of the design phase of engineering design education. We aim to assess the environmental impact of mechanical systems and the related design choices when a power budget is introduced. Moreover, we hypothesise that the power budget constraint will lead to a statistically significant reduction in environmental impact. Furthermore, we wish to evaluate how the power budget influences design strategies made by the students.

The remainder of this paper is structured as follows: Section 2 provides a literature review, outlining existing approaches to sustainability in engineering education and identifying gaps addressed by this study. Section 3 details the methodology, including the study design, implementation of the power budget constraint, and data collection procedures. Section 4 presents the results, with a comparative analysis of environmental impact metrics across semesters. The discussion in Section 5 contextualises the findings, highlighting their implications for engineering education and sustainable design practices. Finally, Section 6 concludes with key insights and directions for future research.

2 Literature Review

The rapid consumption of natural resources and subsequent intensification of greenhouse gas effects has led to heightened global awareness, driving international agendas and policies to compel industries to incorporate more sustainable practices. Moreover, UNESCO and the UN's Sustainable Development

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Goals have articulated the important role of engineering in achieving sustainable forms of development. However, engineering programs often present sustainability as an ancillary concept rather than embedding it within core design principles, leading to a disconnect between theoretical instruction and real-world engineering applications.

Efforts to evaluate sustainability education frequently rely on pre- and post-course surveys, assessing students' awareness rather than their ability to apply sustainability principles in engineering design Bechtel and Yan (2018). These self-reported assessments are prone to bias and fail to measure long-term competency, as students may retain theoretical knowledge without integrating sustainability into practical decision-making Watson et al. (2013). While interventions such as workshops and sustainability-focused courses have demonstrated short-term improvements in environmental awareness, research suggests these effects diminish over time unless reinforced through applied design constraints Bernstein et al. (2012). Collado et al. (2021) found that while structured sustainability workshops led to statistically significant improvements in environmental knowledge, norms, and behaviours, their impact on students' professional practices remained uncertain due to resource intensity, lack of experimental controls, and reliance on self-reported behaviour. These findings underscore the need for sustainability interventions that embed measurable, real-time design constraints, ensuring that sustainability is not merely understood but actively applied in engineering education.

Project-Based Learning has emerged as a vital approach in literature for embedding sustainability into engineering education, providing students with hands-on experience in sustainable design. Raoufi et al. (2019) introduces the ADDIE framework, which structures sustainability evaluation through sequential stages—analysis, design, development, implementation, and evaluation—enabling students to assess environmental and economic impacts. Its multicopter case study standardises sustainability assessment, allowing students to quantify trade-offs in carbon footprint, energy consumption, and material selection. However, its linear structure limits adaptability, restricting iterative refinement, while its predefined design repository, though useful for guidance, constrains creativity and limits unconventional design exploration.

Similarly, Esparragoza et al. (2018) proposes the AID-DS framework, a five-step methodology for evaluating sustainability through indicator selection, baseline measurement, strategy implementation, impact assessment, and comparative analysis. This approach provides a quantifiable evaluation of design decisions, enhancing sustainability-focused decision-making. However, AID-DS remains a post-hoc evaluation tool, assessing sustainability after design choices have been made, rather than embedding it as a real-time design constraint.

Whilst both frameworks introduce structured sustainability assessment methodologies that enable a quantifiable evaluation of design decisions, Bernstein et al. (2012) highlights that current project-based interventions often fail to systematically assess how sustainability is integrated into students' decision-making processes, making it difficult to quantify learning outcomes. Many Project-Based Learning courses assign sustainability-focused projects, such as designing a renewable energy system or an eco-friendly product, which expose students to sustainability concepts but lack a clear, standardised method for evaluating how effectively they integrate sustainability into engineering decision-making. Many of these studies rely on qualitative assessments, such as reports, presentations, and surveys, which offer valuable insights into students' reasoning and design justifications. However, the absence of complementary quantitative metrics measuring sustainability performance makes it difficult to objectively evaluate the tangible impact of sustainability-driven decisions.

This absence of systematic assessment of student projects in literature raises concerns about whether students are genuinely optimising designs for sustainability or merely adhering to project guidelines without deeper engagement. It remains unclear whether they are making sustainability-driven trade-offs or prioritising other factors such as cost and ease of implementation. Furthermore, without empirical validation, it is difficult to determine whether sustainability education leads to measurable improvements in engineering practice, highlighting the need for objective methods to assess how and why sustainability choices are made.

This research aligns with the increasing emphasis on integrating sustainability into engineering education by introducing a power budget as a tangible and measurable design constraint. The power budget embeds environmental considerations directly into the design process, requiring students to account for energy efficiency as an inherent project requirement. By assessing the environmental impact of student projects over two semesters, this study provides empirical insights into the extent to which environmental

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sustainability is actively integrated into design choices.

3 Methodology

3.1 Study Design

This study was conducted over two semesters in the Mechanical Systems Design course at the University of Melbourne. The course focuses on the conceptual engineering design process, including problem clarification, ideation, and prototyping, with an emphasis on semi-autonomous mechanical systems. It also covers mechanical and electro-mechanical machine elements to support system design. Much of the building of these systems takes place in the Telstra Creator Space, a campus makerspace, equipped with laser cutters, 3D printers, and other tools and materials necessary for students to complete their projects. Over one semester, these students would work in teams of 2–3 to design and build an autonomous amusement park ride for two Lego figurines, integrating mechanical motion transfer and electronic safety features. These students consisted of primarily 3rd year undergraduate engineering students, with some master of engineering students. Semester 1 served as the baseline, where students designed mechanical systems without any power budgets. In Semester 2, the same course structure was maintained, but students were required to adhere to the newly introduced power budget requirement.

To assess the impact of this intervention, the environmental impact of these mechanical systems was collected across both semesters. This was achieved by disassembling each project into its original elements, assigning an environmental impact score (EI) to each piece, and calculating the total impact as the sum of these individual scores. The EI of each project was evaluated using a weight-based Life Cycle Assessment (LCA) approach, employing the ReCiPe Endpoint method for its comprehensive assessment of potential damage to human health, ecosystem diversity, and resource scarcity. OpenLCA 1.11 software with the ecoinvent 3.7.1 database was utilised for calculations, with proxies used for components not available in the database. The EI scores used in this study were pre-calculated by another researcher prior to its implementation. Additionally, the majority of semester 1 project EI scores had already been calculated and recorded before this study began. Comparative analyses of EI metrics between semesters aimed to determine whether the intervention led to measurable improvements. The EI scores of electrical components and materials available in the makerspace were tabulated and provided to students.

To further encourage students to minimise environmental impact, the table was formatted with a colour-coded scheme to enhance readability and highlight the relative impact of different materials and components. Green indicated low-impact materials, yellow signified moderate impact, and red denoted highly impactful selections. Colours were assigned based on an item's classification rather than absolute EI per gram. For instance, aluminium is highlighted in red, indicating high impact within its category, despite having a lower per-gram EI than a capacitor, which is highlighted in green. An exception was made for the Arduino and Funduino microcontroller boards, which were not assigned a colour, as every group was required to incorporate one of these boards in their project. A snapshot of the tabulated EI scores is provided below. The complete EI table can be found in the Appendix. Note that the components flange adaptor, small rod adaptor, and large rod adaptor were introduced only in Semester 2 and were not available in Semester 1 for students.



Capacitor	Item	0.76
LED	Item	0.91

Figure 1: Environmental Impact (EI) Table Component Snapshot

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	Steel (Screws, Bolts, Nuts, Sheets, ...)	Weight [g]	0.087
	Aluminium	Weight [g]	0.234

Figure 2: Environmental Impact (EI) Table Building Material Snapshot

3.2 Power Budget

The power budget intervention mandated that all designs maintain a steady-state power consumption limit of 2.5W during operation. This upper limit was derived from the maximum output of a 5V Arduino board powered via USB, supplying up to 500mA. Devices powered solely by an Arduino board through USB were assumed to comply with the 2.5W limit, as this was the maximum power output of a 5V, 500mA USB connection. For devices using external power sources, compliance was judged qualitatively.

3.3 Data Collection

After the conclusion of each semester, student projects were disassembled. These elements were documented in an online spreadsheet similar to the one shown below (note that the figure below is not the actual spreadsheet used), recording details such as the type of part, number of parts, weight, whether the component was static or moving, and, if moving, the type of machine element it represented. Any element found that was absent from the EI table was still added to the spreadsheet, however, their EI would not be recorded. An element was classified as moving if it exhibited motion relative to the platform or base on which the entire system was placed. Conversely, an element was classified as static if it remained stationary relative to the base. Parts were firstly categorised as either components (e.g., Arduinos, resistors, temperature sensors, and motors) or raw materials. Raw materials were further divided into the following six materials that were most common and readily available to students: MDF, timber, acrylic, aluminium, PLA and steel.

	Team 1	Team 2	Team 3	Team 4	Team 5	Team 6	Team 7	Team 8	Team 9	Team 10	Team 11
Arduino or Funduino Board	1	1	1	1	1	1	1	1	1	1	1
IC Drivers											
ProtoShield or Nokia 5110	1	0	0	0	0	0	0	0	0	0	0
Stepper Motor Driver Board	0	1	0	0	0	0	0	0	0	0	0
Motor Drive IC (L293D)	0	1	2	0	0	0	0	0	0	0	0
	0	0	0	0	0	0	0	0	0	0	0
Shift Register (74HC595 or 93DN9YX)	1	0	0	1	0	1	0	1	1	1	1
Motor Shield (Adafruit)	0	0	0	0	1	1	0	1	0	1	0
Breadboards											
Breadboard S	0	0	0	0	0	0	0	0	0	0	0
Breadboard M	1	0	0	0	0	0	0	0	0	0	0
Breadboard L	0	0	0	0	0	0	0	0	0	0	0
Sensors											
Infrared Receiver (VS1838B)	1	0	0	0	0	0	0	0	0	0	0
Light Sensor (Photoresistor)	2	0	0	0	0	0	0	0	0	0	0
Temperature Sensor	1	0	0	0	0	0	0	0	0	0	0
Ultrasonic Sensor (HC-SR04)	1	0	0	0	0	0	0	0	0	0	0
Push Button	1	0	0	0	0	0	0	0	0	0	0

Figure 3: Spreadsheet for Tracking Component and Material Usage

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The EI score of each of these added elements was calculated automatically according to the values in the EI table. Raw materials that individually weighed less than 2g were grouped with other materials that also weighed less than 2g and were of the same type, collectively weighed, and counted as a single component. Once all data were compiled and integrated into the spreadsheet, it was ported to MATLAB for further processing. MATLAB routines were employed to compute several environmental impact metrics. They are as follows:

- The total environmental impact of projects, including the environmental impact of their moving and static elements.
- The material environmental impact distribution within moving elements and its percentage distribution.
- The material percentage distribution within moving elements, highlighting their relative proportions.
- The component environmental impact of projects without connectors (flange and rod adaptors).
- The material environmental impact of projects without steel shafts.

Measuring the total environmental impact provides a holistic understanding of whether the power budget influenced overall sustainability outcomes. Examining the material impact and distribution within moving elements offers insights into design priorities, particularly whether students chose lighter materials to reduce energy demands for steady-state motion. Given that connectors were introduced only in Semester 2 and exhibit a disproportionately high environmental impact, their exclusion from component-level analysis prevents result distortion and allows for a more accurate assessment of design adaptations across semesters. Likewise, steel shafts, which became more prevalent following the introduction of connectors, were encouraged as a realistic design choice but also carry a high EI. By evaluating material impact with and without both steel shafts and connectors, this study provides a clearer understanding of how these components influenced overall sustainability outcomes.

From this, data from 17 teams in Semester 1 and 39 teams in Semester 2 were recorded and used for data analysis. Some projects were excluded from data collection as they were retained for display purposes.

3.4 Data Analysis

To select the most suitable hypothesis test, the normality of the data was assessed. Depending on the results, either the independent-samples t-test (for normally distributed data) or the Mann-Whitney U-test (for non-normal data) was applied.

Normality was evaluated both visually and analytically. Histogram and Quantile-Quantile (Q-Q) plots showed the data's distribution whilst the Shapiro-Wilks test was used to statistically confirm normality. A p-value less than 0.05 in the Shapiro-Wilk test indicated the rejection of the null hypothesis, suggesting the data was not normally distributed. Other normality tests can be used, however, the Shapiro-Wilk test is particularly suited for small sample sizes of less than 50 (Mishra et al., 2019).

4 Results

4.1 Normality Tests

Normality testing was conducted to determine the appropriate statistical methods for comparing environmental impact (EI) metrics between semesters. To maintain conciseness, this section includes only the most meaningful and illustrative plots. Additional datasets and plots are provided in the Appendix for reference.

4.1.1 Project Material and Component Environmental Impact (EI) Overview

Figures 4 and 5 show the histogram and Q-Q plot for the material and component EI of Semester 1 projects. The histogram reveals a right-skewed distribution, while the Q-Q plot shows moderate deviations from the reference line at the tails, suggesting non-normality. The Shapiro-Wilk test results for Semester 1 data are summarised in Table 1. The null hypothesis of normality was rejected for all datasets except moving material EI ($p = 0.07343$), indicating that most data was not normally distributed.

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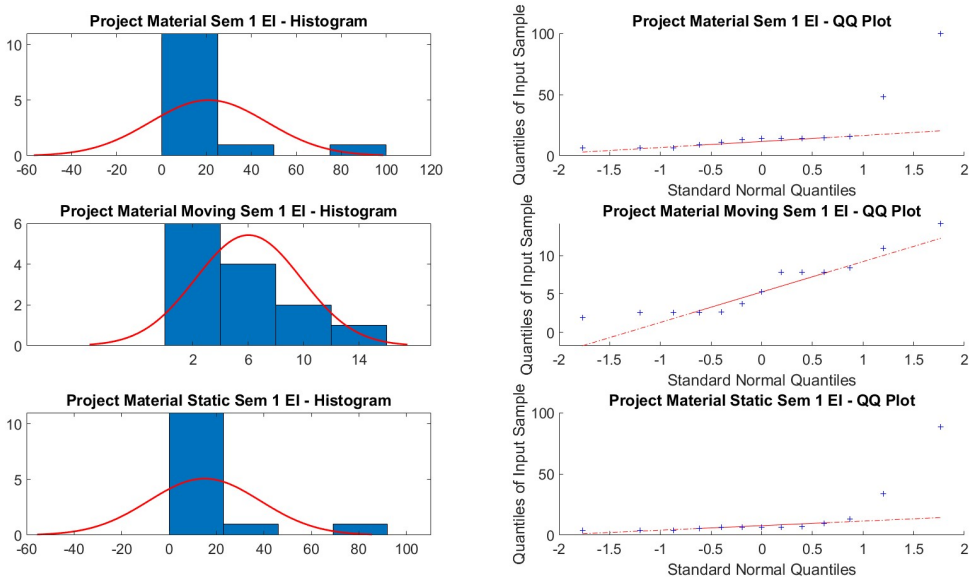


Figure 4: Histogram and QQ Plot of Project Materials Semester 1

Table 1: Shapiro-Wilks Test Results Semester 1 for Project Material and Component

Dataset	p	Normality
Total Material EI	5.294×10^{-5}	False
Moving Material EI	0.07343	True
Static Material EI	2.399×10^{-5}	False
Total Component EI	0.003976	False
Moving Component EI	1.096×10^{-5}	False
Static Component EI	0.001329	False

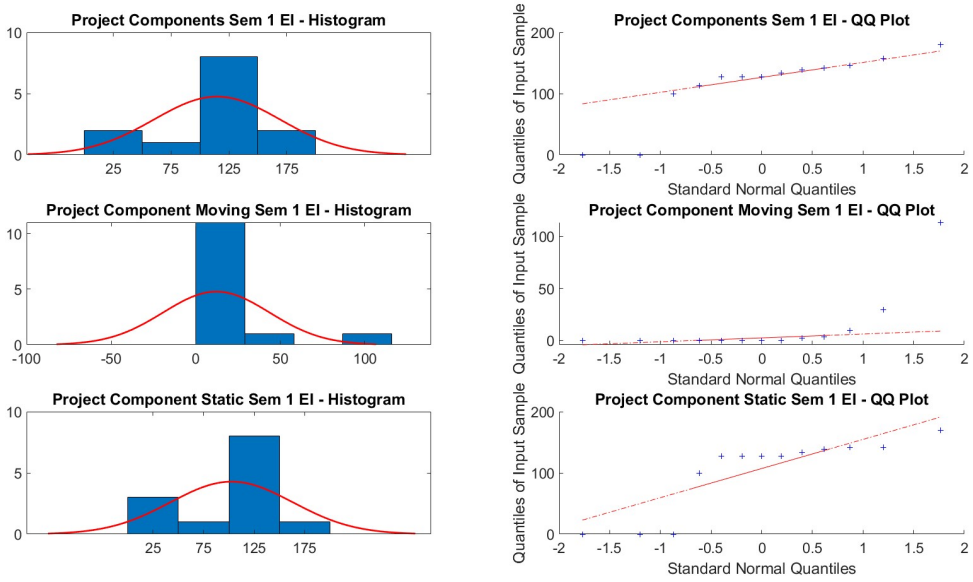


Figure 5: Histogram and QQ Plot of Project Components Semester 1

Plots and normality test results for Semester 2 data are provided in Appendix 6. The findings for Semester

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2 were consistent with those of Semester 1, with all datasets exhibiting non-normal distributions.

Table 2: Shapiro-Wilks Test Results for Project Material and Component Overview Semester 2

Dataset	p	Normality
Total Material EI	0.001513	False
Moving Material EI	0.01503	False
Static Material EI	0.0001427	False
Total Component EI	1.118×10^{-5}	False
Moving Component EI	7.242×10^{-7}	False
Static Component EI	9.460×10^{-6}	False

Based on the results of the normality tests, non-parametric statistical tests (Mann-Whitney U test) were deemed appropriate for comparing EI metrics between semesters.

4.1.2 Material EI Distribution as Moving Elements

Both the histogram and Q-Q plots for the moving material EI of both semesters 1 and 2 projects demonstrate a right-skewed distribution and significant deviation from the reference line at the tails. The Shapiro-Wilk test results for both Semesters 1 and 2 are summarised below, with the null hypothesis of normality being rejected for all datasets, indicating that the data was not normally distributed. For this reason, the Mann-Whitney U test will be used in comparing these datasets.

Table 3: Shapiro-Wilks Test Results for Semester 1 Moving Materials

Material	p	Normality
Sem 1 MDF	0.03637	False
Sem 1 Timber	1.296×10^{-5}	False
Sem 1 Acrylic	3.704×10^{-5}	False
Sem 1 PLA	0.01065	False
Sem 1 Aluminium	NaN	False
Sem 1 Steel	4.114×10^{-4}	False

Table 4: Shapiro-Wilks Test Results for Semester 2 Moving Materials

Material	p	Normality
Sem 2 MDF	9.522×10^{-6}	False
Sem 2 Timber	1.565×10^{-9}	False
Sem 2 Acrylic	7.644×10^{-8}	False
Sem 2 PLA	8.078×10^{-7}	False
Sem 2 Aluminium	NaN	False
Sem 2 Steel	8.079×10^{-5}	False

4.1.3 Material Percentage Distribution in Moving Elements

Similar to Section 4.1.2, aluminium usage in both Semesters 1 and 2 is highly skewed, with nearly all values concentrated at zero. PLA and timber exhibit right-skewed distributions in their histograms, with deviations from normality evident in the tails of their Q-Q plots. MDF usage in Semester 1 follows a bell-shaped distribution, while Semester 2 shows a more evenly spread distribution, with the Q-Q plot of both semesters indicating near-normality. Steel follows a bell-shaped distribution in Semester 1, whereas in Semester 2, the distribution is more dispersed and less symmetric. The Q-Q plot further confirms greater variability in steel usage in Semester 2 compared to Semester 1. The Shapiro-Wilk test results for Semester 1 data are summarised in Table 5. The null hypothesis of normality was rejected for all datasets except MDF ($p = 0.4026$) and Steel (0.2808) percentage totals.

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Table 5: Shapiro-Wilks Test Results for Semester 1 Material Percentage Totals

Material	p	Normality
Sem 1 MDF Percentage Total	0.4026	True
Sem 1 Timber Percentage Total	4.406×10^{-6}	False
Sem 1 Acrylic Percentage Total	2.262×10^{-4}	False
Sem 1 Aluminium Percentage Total	NaN	False
Sem 1 PLA Percentage Total	3.356×10^{-4}	False
Sem 1 Steel Percentage Total	0.2808	True

Similarly to the data of semester 1, the null hypothesis of normality was rejected for all datasets except MDF ($p = 0.1392$) and Steel (0.1709) percentage totals.

Table 6: Shapiro-Wilks Test Results for Semester 2 Material Percentage Totals

Material	p	Normality
Sem 2 MDF Percentage Total	0.1392	True
Sem 2 Timber Percentage Total	7.199×10^{-10}	False
Sem 2 Acrylic Percentage Total	1.137×10^{-7}	False
Sem 2 Aluminium Percentage Total	NaN	False
Sem 2 PLA Percentage Total	7.407×10^{-6}	False
Sem 2 Steel Percentage Total	0.1709	True

Based on the results of the normality tests, non-parametric statistical tests (Mann-Whitney U test) were deemed appropriate for comparing percentage totals for Timber, Acrylic, PLA and aluminium between semesters 1 and 2. Independent t-test is used for comparing MDF and steel datasets between semesters 1 and 2 since those datasets were found to be normally distributed.

4.1.4 Component Environmental Impact of Projects Without Connectors

The histogram for components without connectors demonstrates skewness, with the Q-Q plot having moderate deviation from the reference line at the tails. The Shapiro-Wilk test results are summarised below, with the null hypothesis of normality being rejected for all datasets, indicating that the data was not normally distributed. For this reason, the Mann-Whitney U test will be used in comparing these datasets.

Table 7: Normality Test Results for Semester 2 Component EI Data Without Connectors

Dataset	p	Normality
Total Component EI	1.27×10^{-5}	False
Moving Component EI	1.02×10^{-6}	False
Static Component EI	1.33×10^{-5}	False

4.1.5 Material Environmental Impact Without Steel Shafts

The histogram for materials without steel shafts does appear to roughly follow a bell curve, with the histogram pertaining to semester 2 moving material demonstrating right skewness. Q-Q plots demonstrate moderate deviation from the reference line at the tails. The Shapiro-Wilk test results are summarised below, with the null hypothesis being rejected for all datasets asides for moving material EI for semester 1. Based on these results, the Mann-Whittney U Test will be used in comparing these datasets.

Table 8: Normality Test Results for Material EI Data

Dataset	p	Normality
Sem 2 Total Material EI	0.00936	False
Sem 2 Moving Material EI	0.00803	False
Sem 1 Total Material EI	5.09×10^{-5}	False
Sem 1 Moving Material EI	0.343	True

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4.2 Mann-Whitney U Test

4.2.1 Project Material and Component Environmental Impact (EI) Overview

The Mann-Whitney U test was run to determine if there were any differences in EI for the following categories: 1) Total Material EI; 2) Moving Material EI; 3) Static Material EI; 4) Total Component EI; 5) Moving Component EI; 6) Static Component EI. For each category, the scores were not statistically significantly different.

Table 9: Project Material and Component EI Mann-Whitney U Test Results

Category	Sem 1 Rank	Sem 2 Rank	U_{S1}	U_{S2}	z	p	H_0 Rejected
Total Material EI	21.077	27.684	311	183	1.373	0.170	N
Moving Material EI	26.000	26.000	247	247	-0.011	1.000	N
Static Material EI	19.538	28.211	331	163	1.805	0.071	N
Total Component EI	25.000	26.342	260	234	0.270	0.787	N
Moving Component EI	25.615	26.132	252	242	0.105	0.916	N
Static Component EI	23.038	27.013	285.5	208.5	0.822	0.411	N

The average EI per project rose, with the average EI of materials rising by 0.1 and the average EI of components rising by 9.14. Breaking down the project data into its moving and static constituents, The average EI of moving materials per project increased from 6.02 to 6.72, with their relative contribution to total material EI rising from 28.66% to 31.85%. In contrast, the average EI of moving components per project dropped from 10.62 to 1.78, with the proportion of total component EI attributed to moving components decreasing from 10.62% to 1.78%.

For static elements, the average EI of static materials per project experienced a slight reduction from 14.98 to 14.32, with their proportion relative to total material EI decreasing from 71.34% to 67.88%. However, static components exhibited a notable increase in average EI to 121.69, with their proportion of total component EI increasing from 89.52% to 98.22%.

Whilst these results are not statistically significant, the reduction in the average EI of moving components in semester 2 is interesting. The results may indicate that students have opted to avoid heavier, more power hungry and high EI mechatronics components to meet the introduced power budget. Additionally, students might have relied on alternative drive mechanisms such as gear boxes instead of high torque motors.

Table 10: Project Material and Component EI Statistics for Semesters 1 and 2

Category	Total EI	Average EI
Sem 1 Materials	273.02	21.00
Sem 2 Materials	801.88	21.10
Sem 1 Components	1491.87	114.76
Sem 2 Components	4708.19	123.90

Table 11: Project Material and Component Moving and Static EI Statistics for Semesters 1 and 2

Category	M_{Total}	M_{Avg}	Moving (%)	S_{Total}	S_{Avg}	Static (%)
Sem 1 Materials	78.24	6.02	28.66	194.78	14.98	71.34
Sem 2 Materials	255.39	6.72	31.85	544.32	14.32	67.88
Sem 1 Components	158.39	12.18	10.62	1335.52	102.73	89.52
Sem 2 Components	83.90	2.21	1.78	4624.29	121.69	98.22

4.2.2 Material EI Distribution as Moving Elements

Using the Mann-Whitney U Test to compare moving material EI between semesters, it was found that the scores for all materials were not statistically significantly different. MDF ($p = 0.854$), timber ($p = 0.839$) and steel ($p = 0.829$) all had relatively high p values, indicating that the average moving EI of these materials per project was very similar between semester 1 and semester 2. The p-values for Acrylic

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(0.189) and PLA (0.321) indicate more variability in their distributions. Aluminium exhibited identical rankings across semesters, resulting in no measurable variation, and thus statistical calculations could not be performed.

Table 12: Mann-Whitney U Test Results for Material EI Distribution as Moving Elements

Category	Sem 1 Rank	Sem 2 Rank	U_{Sem1}	U_{Sem2}	z	p	H_0 Rejected
MDF EI	25.308	26.237	256	238	0.184	0.854	N
Timber EI	25.462	26.184	254	240	0.203	0.839	N
Acrylic EI	30.154	24.579	193	301	1.313	0.189	N
Aluminium EI	26.000	26.000	247	247	-Inf	NaN	N
PLA EI	29.423	24.829	202.5	291.5	0.992	0.321	N
Steel EI	26.808	25.724	236.5	257.5	0.216	0.829	N

4.2.3 Material Percentage Distribution in Moving Elements

Observing Table 13, the Mann-Whitney U test results indicate no statistically significant differences in the percentage distribution of timber, acrylic, PLA, and aluminium between Semesters 1 and 2. Results are similar to Table 12, where timber (p = 0.815) had the greatest consistency between semesters, whereas acrylic (p = 0.215) and PLA (p = 0.392) suggests minor fluctuations, potentially reflecting design optimisations under the power budget constraint, albeit insufficient to confirm a meaningful shift.

Table 13: Mann-Whitney U Test Results for Timber, Acrylic, Aluminium, and PLA Percentage Totals

Category	Sem 1 Rank	Sem 2 Rank	U_{Sem1}	U_{Sem2}	z	p	H_0 Rejected
Timber Percentage Total	25.385	26.211	255	239	0.234	0.815	N
Acrylic Percentage Total	29.923	24.658	196	298	1.240	0.215	N
Aluminium Percentage Total	26.000	26.000	247	247	-Inf	NaN	N
PLA Percentage Total	28.962	24.987	208.5	285.5	0.857	0.392	N

The independent t-test indicated no significant difference in the average percentage of both moving MDF and steel. Steel (p = 0.915) had a high p-value, indicating an almost complete lack of evidence for a meaningful difference between the two semesters. The p-value for MDF (p=0.203) is relatively lower than that of steel but still above the 0.05 threshold, suggesting weak evidence against the null hypothesis. This may indicate a potential trend or shift in MDF usage, but the effect is not strong enough to be considered statistically significant.

Table 14: Independent t-Test Results for MDF and Steel

Material	Mean ± SD (Sem 1)	Mean ± SD (Sem 2)	Δ	95% CI	$t(df), p$
MDF EI	33.06 ± 19.15	41.87 ± 25.79	8.81	(-22.66, 5.04)	$t(28.02) = -1.303, p = 0.203$
Steel EI	38.67 ± 17.17	39.33 ± 23.34	0.65	(-13.11, 11.80)	$t(28.29) = -0.108, p = 0.915$

Whilst the data itself is not statistically significant, it still reveals notable shifts in material usage. The mean EI of MDF increased from 1.90 to 2.45 per project, with its proportion of total material EI increasing from 33.06% to 41.87%. This suggests that MDF played a more prominent role in student projects when constrained by the power budget. Conversely, acrylic's contribution to total material EI dropped from 7.04% to 1.79%, with its mean EI decreasing from 0.47 to 0.06 per project, indicating a significant reduction in its use as a moving element in student designs.

One possible reason for this shift is that MDF and acrylic are the only two materials suitable for laser cutting. Given that MDF has a lower EI than acrylic while also being lighter, with a density of 0.6–0.8 g/cm^3 compared to 1.18–1.20 g/cm^3 for acrylic, students may have preferred MDF to reduce environmental impact while maintaining manufacturability.

The data also indicates a slight increase in steel usage, with its mean EI per project rising from 2.47 to 2.98. However, its proportion of total material EI remained stable at around 39%, suggesting that steel continued to be a favoured structural component.

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PLA usage remained relatively consistent, with its mean EI increasing slightly from 1.08 to 1.18 per project, while its proportion of total material EI decreased from 17.30% to 15.30%. Timber, despite having the lowest EI score among all raw materials, saw a notable decline, with its proportion of total material EI dropping from 3.93% to 1.72%. As a machine element, it was largely absent in gears for both semesters and was negligible in shafts, with an EI of zero in semester 1 and only 2.18% in semester 2. This suggests that timber was largely phased out, likely due to a lack of availability for laser cutting, and possible substitution by stronger materials such as steel.

Table 15: Mean and Average Percentage Comparison for Semesters 1 and 2

Material	Mean (Sem 1)	Mean (Sem 2)	Avg % (Sem 1)	Avg % (Sem 2)
MDF	1.90	2.45	33.06	41.87
Timber	0.10	0.05	3.93	1.72
Acrylic	0.47	0.06	7.04	1.79
Aluminium	0.00	0.00	0.00	0.00
PLA	1.08	1.18	17.30	15.30
Steel	2.47	2.98	38.67	39.33

In contrast, steel remained the dominant material for shafts, with its usage increasing significantly. The data shows that steel accounted for 97.73% of the total shaft material EI in Semester 2, up from 77.51% in Semester 1. The average EI contribution of moving steel shafts per project also increased from 1.18 to 2.04. This rise in usage and EI can be attributed to the introduction of rod and flange adapters into the makerspace, which simplified the process of connecting shafts. The ease of assembly likely motivated students to use steel more frequently, despite its higher environmental impact.

This same argument could be used to justify an increase in timber shaft usage; however, timber's proportion of total shaft material EI remained negligible. This suggests that students may have found timber impractical due to its lower strength, making it less suitable for load-bearing applications despite the availability of connectors. Furthermore, the steel shafts were conveniently either the same or similar size to the adaptors introduced in Semester 2, whereas the timber shafts available to students, in the form of dowels, were often too thick to be easily integrated. This mismatch in dimensions likely discouraged students from using timber shafts, further reinforcing the preference for steel.

Table 16: Shaft Moving Material Usage and Environmental Impact (EI) for Semesters 1 and 2

Shaft Material	Sem 1 Avg EI	Sem 2 Avg EI	Sem 1 Moving	Sem 2 Moving	Sem 1 (%)	Sem 2 (%)
MDF	0.00	0.00	0.00	0.07	0.00	0.09
Timber	0.00	0.05	0.00	1.73	0.00	2.18
Acrylic	0.00	0.00	0.00	0.00	0.00	0.00
PLA	0.00	0.00	0.00	0.00	0.00	0.00
Steel	1.18	2.04	15.32	77.51	100.00	97.73

Comparing gear usage across Semesters 1 and 2, MDF remained the dominant material, with a substantial increase in its EI in Semester 2. This trend was observed across all gear materials. The rise in gear usage as a moving element may be attributed to the increased emphasis on energy efficiency under the power budget, prompting students to prioritise mechanically efficient motion transmission methods. The preference for lighter materials, such as MDF over acrylic further reinforces this shift, as students aimed to minimise weight and inertia while maintaining functional performance. PLA's customisability through 3D printing likely made it an attractive alternative for tailored gear designs.

Table 17: Gear Moving Material Usage and Environmental Impact (EI) for Semesters 1 and 2

Gear Material	Sem 1 Avg EI	Sem 2 Avg EI	Sem 1 Moving	Sem 2 Moving	Sem 1 (%)	Sem 2 (%)
MDF	0.38	1.16	4.99	44.11	100.00	71.05
Acrylic	0.00	0.02	0.00	0.69	0.00	1.11
PLA	0.00	0.45	0.00	17.29	0.00	27.84

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4.2.4 Component Environmental Impact of Projects Without Connectors

Using the Mann-Whitney U Test to compare the component environmental impact of projects without connectors between semesters 1 and 2, it was found that the scores were not statistically significantly different. The high p-value for Total Component EI (0.868) suggests near-complete overlap between the distributions. The Moving Component EI (p = 0.166) whilst not being statistically significantly different, has a relatively lower p-value compared to both static and total component EI.

Table 18: Mann-Whitney U Test Results for Component EI Semester 1 vs Semester 2 No Connector

Category	Sem 1 Rank	Sem 2 Rank	U_{Sem1}	U_{Sem2}	z	p	H_0 Rejected
Total Component EI	16.615	17.250	135	125	0.166	0.868	N
Moving Component EI	19.308	15.500	100	160	1.385	0.166	N
Static Component EI	15.423	18.025	150.5	109.5	0.738	0.461	N

Given that connector EI is high relative to other components, it is of particular interest to examine whether the inclusion of connectors in semester 2 significantly contributed to its overall component EI. To analyse this, the Mann-Whitney U Test was applied to semester 2 components to assess whether the addition of connectors had a statistically significant impact on EI scores.

The results indicate that Total Component EI (p = 0.775) and Static Component EI (p = 0.915) did not exhibit statistically significant differences, suggesting that the presence of connectors did not substantially alter the environmental impact of static components. However, the statistically significant difference in Moving Component EI (p = 0.022) suggests that the inclusion of connectors (flange and rod adaptors) meaningfully altered the distribution of environmental impact. Furthermore, whilst only 51% of groups from semester 2 used at least one or more connectors in their project, it was shown that connectors had an extreme impact on average moving component EI per project (M_{Avg}), shifting this value from 0.49 to 2.21 when groups using connectors are considered.

Table 19: Semester 2 Component EI Metrics (With vs. No Connector)

Category	Tot EI	T_{Avg} EI	M_{Tot}	M_{Avg}	Move (%)	S_{Tot}	S_{Avg}	Stat (%)
S2 Comp (Conn.)	4708.19	123.90	83.90	2.21	1.78	4624.29	121.69	98.22
S2 Comp (No Conn.)	2468.96	123.45	9.89	0.49	0.40	2459.07	122.95	99.60

Table 20: Mann-Whitney U Test Results for Sem 2 Component EI (Connector vs. No Connector)

Category	With Rank	Without Rank	U_{Sem1}	U_{Sem2}	z	p	H_0 Rejected
Total Component EI	29.974	28.600	362	398	0.286	0.775	N
Moving Component EI	32.763	23.300	256	504	2.288	0.022	Y
Static Component EI	29.684	29.150	373	387	0.106	0.915	N

4.2.5 Material Environmental Impact Without Steel Shafts

Using the Mann-Whittney U Test to compare material environmental impact of projects without steel shafts between semesters 1 and 2, it was found that the scores for all materials were not statistically significant difference in total or moving material EI between semesters after excluding steel shafts, as evidenced by high p-values (0.206 and 0.837).

Table 21: Mann-Whitney U Test Results for Material EI Without Steel Shafts

Category	Sem 1 Rank	Sem 2 Rank	U_{Sem1}	U_{Sem2}	z	p	H_0 Rejected
Total Material EI	21.462	27.553	306	188	1.265	0.206	N
Moving Material EI	26.769	25.737	237	257	0.205	0.837	N

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5 Discussion

Contrary to the initial hypothesis that the constraint would lead to lower EI scores in semester 2 as opposed to semester 1, total EI scores in Semester 2 were slightly higher than in Semester 1. Moreover, results between semester 1 and semester 2 were not statistically significant. This indicates that projects may already have been sufficiently lightweight prior to the intervention, consuming less than 2.5W at steady state. Instead of further weight reduction, the constraint appears to have shifted design priorities, particularly in material distribution and energy-efficient motion transmission. These findings suggest that rather than simply driving reductions in EI, the power budget may have shaped design trade-offs, encouraging students to prioritise mechanical efficiency and material selection.

The exclusion of connectors in the comparison of semester 1 and semester 2 project component EI was not statistically significantly different. However, the moving component EI result between semester 2 project components with and without connectors was statistically significant, suggesting their substantial contribution to environmental impact. Despite their relatively high EI, 51% of student groups opted to use at least one connector, likely due to their practical advantages in securely joining rods. This decision was likely influenced by the fact that rod and flange adaptors, along with steel shafts, were encouraged by the teaching staff for their practicality and alignment with real-world machine design practices, where robust and reliable connections are necessary. Furthermore, while alternative solutions, such as wooden shafts with custom interfaces, could have been explored, it could also be the case that functionality and ease of assembly outweighed environmental considerations, as designing custom alternatives may have been perceived as too time-intensive within the project constraints. Similarly, the exclusion of steel shafts in the statistical analysis did not reveal a significant difference in total or moving material EI between semesters. Combined with the findings on connectors, this suggests that students may not have fully understood how to integrate the power budget into their design decisions, as the continued preference for high-EI steel shafts, despite the constraint, indicates limited adaptation in material selection.

Given that this iteration of the Mechanical Systems Design course is relatively new and has only been coordinated by the same instructor for the past three years, some observed shifts in design strategy may be influenced by factors beyond the power budget, such as evolving instructional approaches or variations in student cohort dynamics. Additionally, minor methodological limitations arose during data collection. Despite guidelines discouraging adhesive use, some students still incorporated adhesives, which could not be removed from materials. Consequently, when weighing these materials, the adhesive's weight was included in the total material weight. However, given the small quantity of adhesive used and the impracticality of removal, its environmental impact was assumed negligible. Similarly, certain materials, such as string, were excluded from EI calculations due to the absence of corresponding EI values in the provided dataset. However, as these items were used infrequently, and their EI calculation would require considering factors beyond weight, such as length, their overall impact on the results is assumed to be minimal.

As part of the Mechanical Systems Design course, students were required to produce reports detailing their design decisions in alignment with project requirements and self-defined targets. A review of anonymised reports revealed that while teams justified their choices in terms of EI and other general environmental considerations, rarely did teams cite the power budget as a determining factor in their decision-making, indicating a disconnect between the imposed requirement and students' perceived priorities. Amongst the teams that did consider the power budget, their considerations were often incomplete, with many teams only calculating power requirements only for the movement element, neglecting power drawn by the electrical components. Only a few teams empirically measured total power consumption in steady-state operation.

Across both semesters, MDF emerged as the dominant material, preferred for its lower EI relative to acrylic and PLA, aligning with the quantitative findings. PLA remained popular, not necessarily for sustainability reasons but due to its suitability for complex geometries. While many teams aimed to reduce material usage for environmental sustainability, justifications were often vague, with statements such as "reasonably low EI" lacking quantifiable benchmarks. A few teams did not address environmental impact at all, suggesting that sustainability considerations were not consistently integrated into decision-making.

From these reports, the exclusion of reused components from quantitative EI analysis emerges as a clear limitation of this study, despite several teams citing reuse as a core sustainability strategy and instructors encouraging this practice. Since reused components were not factored into the quantitative

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data analysis, this may have influenced how students framed their justifications, as they saw reuse as a valid sustainability approach that was not necessarily reflected in measured EI reductions.

Nevertheless, these findings contribute to the broader discourse on sustainability in engineering education by demonstrating that embedded constraints, rather than explicit sustainability mandates, can influence student decision making. Unlike traditional pedagogical approaches that present sustainability as an abstract principle, this study illustrates how structured constraints can drive shifts in design strategies.

However, this study does not evaluate whether the constraint fosters long-term pro-environmental behaviours among students. Future research could explore alternative constraints, such as enforcing specific material choices or incorporating lifecycle considerations, to further examine how structured interventions shape engineering decision-making. These areas present valuable opportunities for expanding the integration of sustainability within engineering curricula.

6 Conclusions

This study examined whether introducing a power budget constraint in the Mechanical Systems Design course would lead to lower environmental impact (EI) scores by encouraging lighter, energy-efficient designs. Contrary to expectations, no statistically significant difference in EI scores was found between Semester 1 (unconstrained) and Semester 2 (power-constrained), suggesting that projects were already operating within the 2.5W limit. However, the constraint influenced design trade-offs, shifting material selection rather than purely reducing EI. Increased gear usage and the preference for MDF and PLA over acrylic suggest that students prioritised energy efficiency, while the rise in steel shaft usage highlights structural integrity considerations. These findings demonstrate that embedded constraints, rather than explicit sustainability mandates, could potentially guide decision making in engineering education. Future research could explore alternative constraints or assess long-term impacts on student design behaviour to further refine sustainability-focused interventions.

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Appendix: Environmental Impact (EI) Table

Electronic Components			
	Name	**Unit**	**Environmental Impact**
Boards and Chips			
	Arduino or Funduino Board	Item	79.85
	Motor Drive IC (L293D)	Item	27.70
	Shift Register (74HC595 or 93DN9YX)	Item	28.52
	Stepper Motor Driver Board	Item	38.79
	Motor Drive IC (L293E)	Item	41.63
	Motor Shield (Adafruit)	Item	45.76
	Breadboard Small	Item	1.39
	Breadboard Medium	Item	4.00
	Breadboard Large	Item	7.67
Sensors			
	Light Sensor (Photoresistor)	Item	0.21

Figure 6: EI Table Page 1

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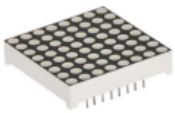
	Temperature Sensor	Item	0.22
	Infrared Receiver (VS1838B) + Remote Control	Item	6.25
	Ultrasonic Sensor (HC-SR04)	Item	8.12
Switches			
	Push Button	Item	1.16
	Toggle Switch	Item	4.48
	Potentiometer	Item	5.66
Displays			
	Piezo Buzzer	Item	1.70
	1-Digit Display	Item	2.59
	4-Digit Display	Item	9.52
	LED 8X8 Matrix	Item	10.65
	LCD Display	Item	37.42
Batteries and Battery-Holders			
	AAA Battery	Item	3.38
	AA Battery	Item	6.73

Figure 7: EI Table Page 2

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	9V Battery	Item	12.78
	9V Battery Snap Clip	Item	0.24
	Battery Holder 9V (box)	Item	0.92
	3 x AAA + Battery Holder	Item	11.24
	2 x AA + Battery Holder	Item	14.66
	4 x AA + Battery Holder	Item	28.12
	8 x AA + Battery Holder	Item	57.38
Motors			
	Servo Motor (SG90)	Item	3.47
	DC Motor (3V)	Item	9.83
	Stepper Motor (28BYJ-48) + Driver Board	Item	11.60 + 39.79
	Stepper Motor (NEMA 17) + Motor Shield (Adafruit)	Item	64.60 + 45.76
Basic Circuit Components			
	Diode	Item	0.32
	Resistor	Item	0.41

Figure 8: EI Table Page 3

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	Capacitor	Item	0.76
	LED	Item	0.91
	MOSFET Transistor	Item	1.65
Connectors			
	Jumper Wire	Item	0.22
	Flange Adaptor	Item	0.94
	Rod Adaptor Small	Item	1.19
	Rod Adaptor Large	Item	1.92

Building Materials			
	Name	**Unit**	**Environmental Impact**
	Timber	Weight [g]	0.021
	MDF (Medium Density Fibreboard)	Weight [g]	0.023
	PLA (3D printed)	Weight [g]	0.056
	Acrylic	Weight [g]	0.084

Figure 9: EI Table Page 4

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	Steel (Screws, Bolts, Nuts, Sheets, ...)	Weight [g]	0.087
	Aluminium	Weight [g]	0.234

Figure 10: EI Table Page 5

Appendix: Normality Testing Results

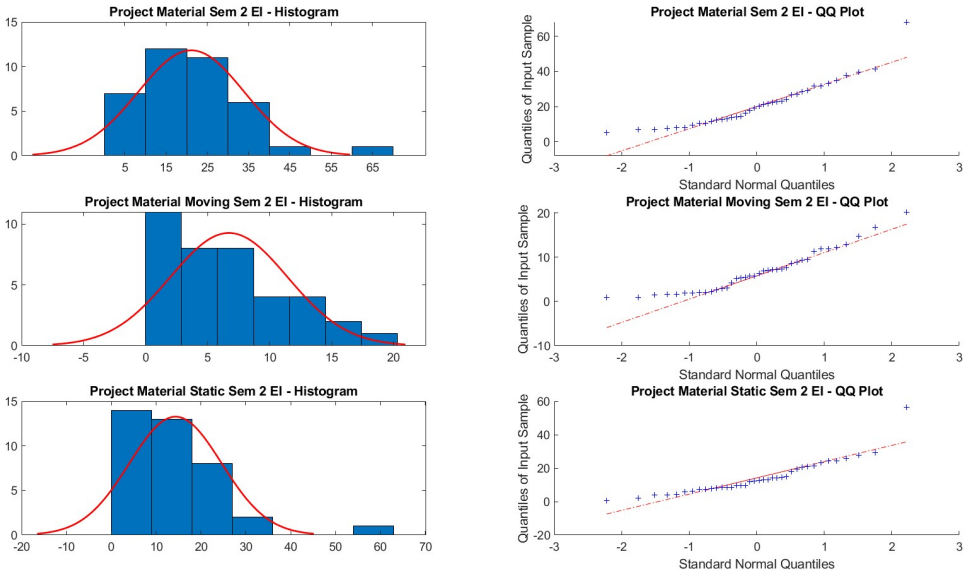


Figure 11: Histogram and QQ Plot of Project Materials Semester 2

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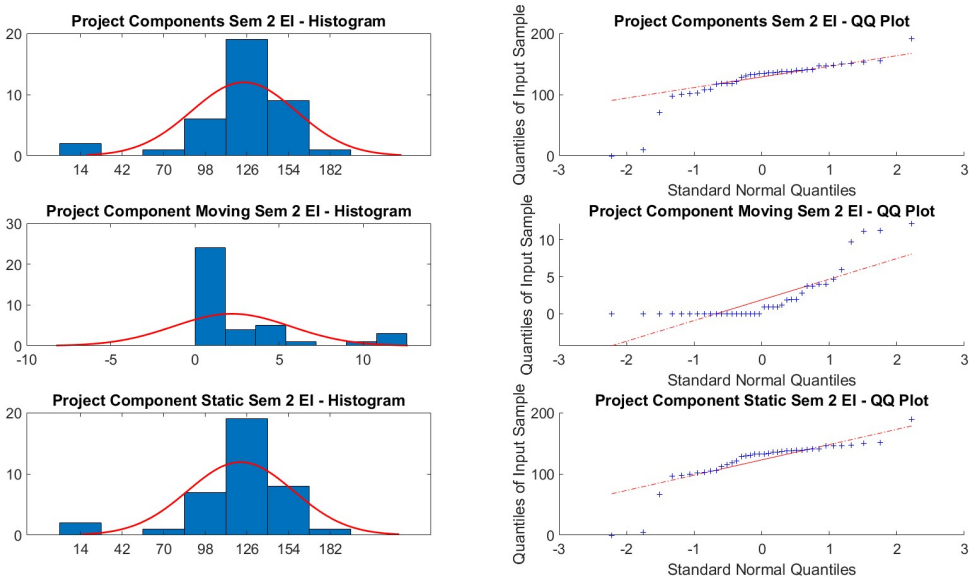


Figure 12: Histogram and QQ Plot of Project Components Semester 2

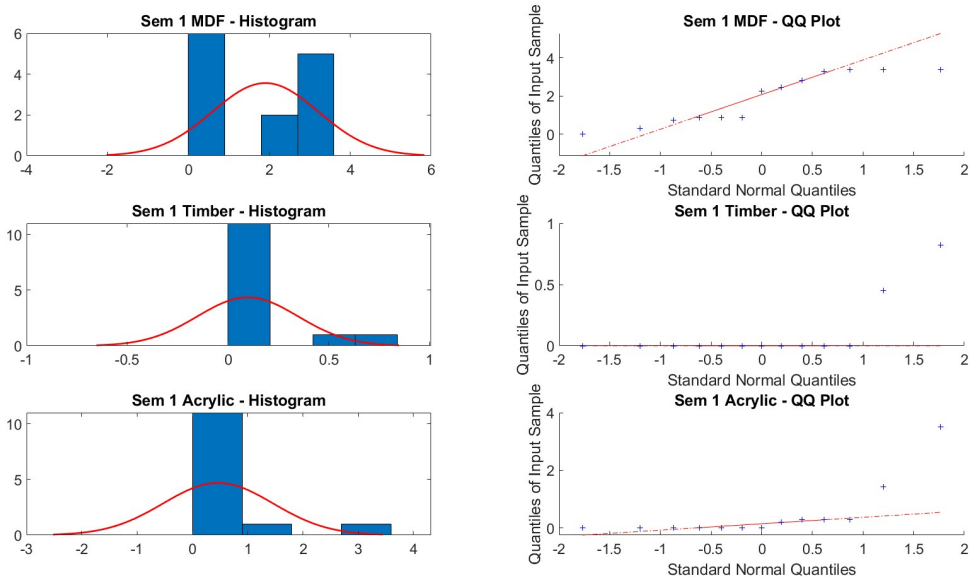


Figure 13: Histogram and QQ Plot of Moving MDF Timber Acrylic EI Semester 1

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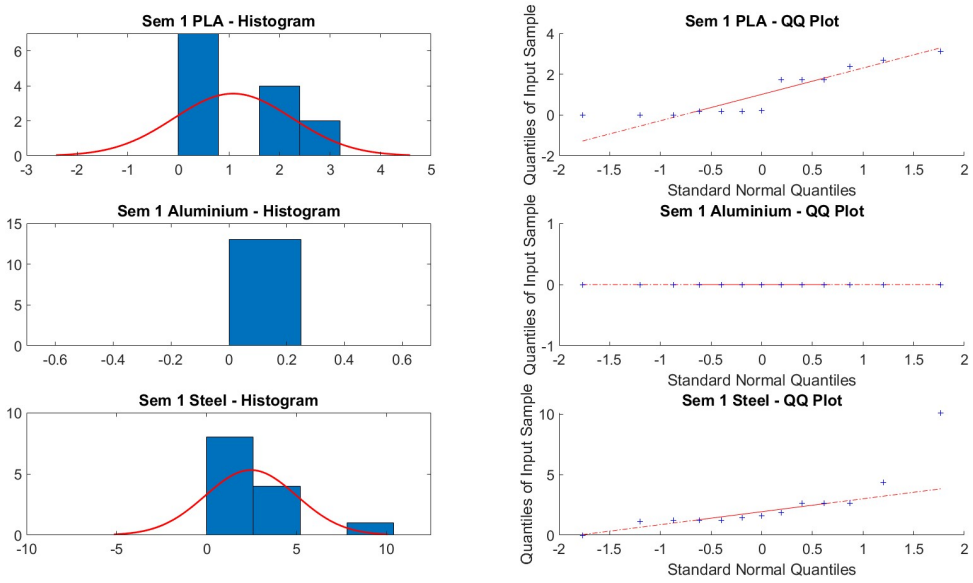


Figure 14: Histogram and QQ Plot of Moving PLA Aluminium Steel EI Semester 1

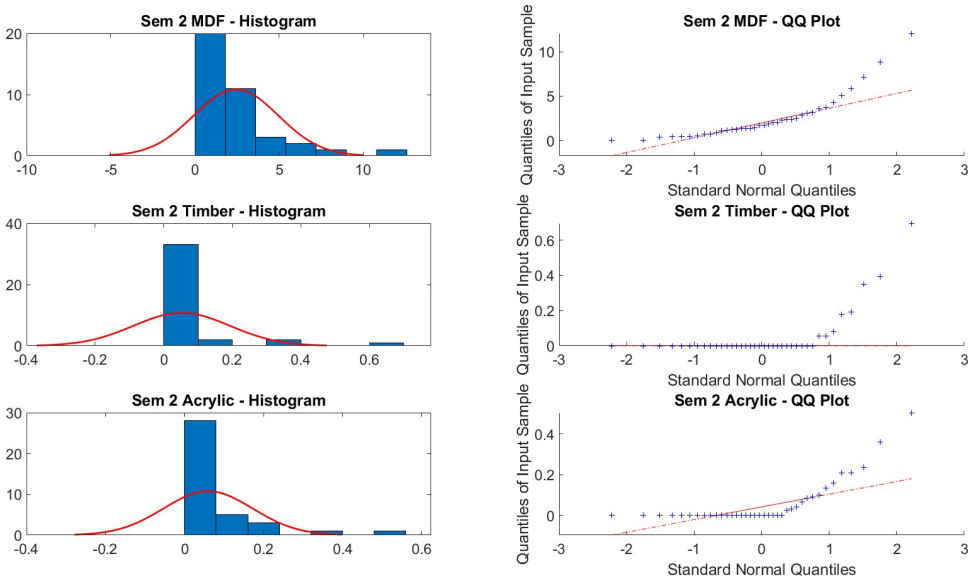


Figure 15: Histogram and QQ Plot of Moving MDF Timber Acrylic EI Semester 2

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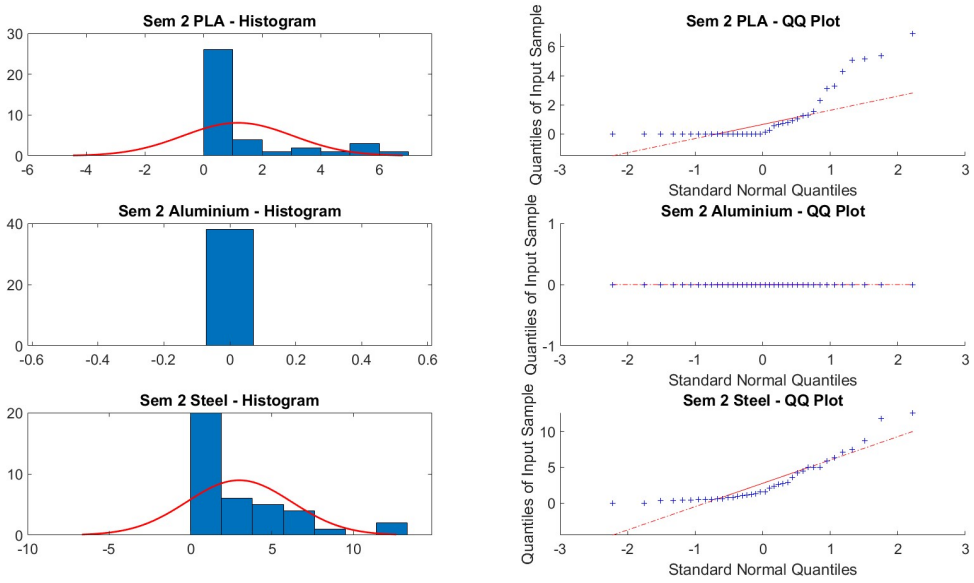


Figure 16: Histogram and QQ Plot of Moving PLA Aluminium Steel EI Semester 2

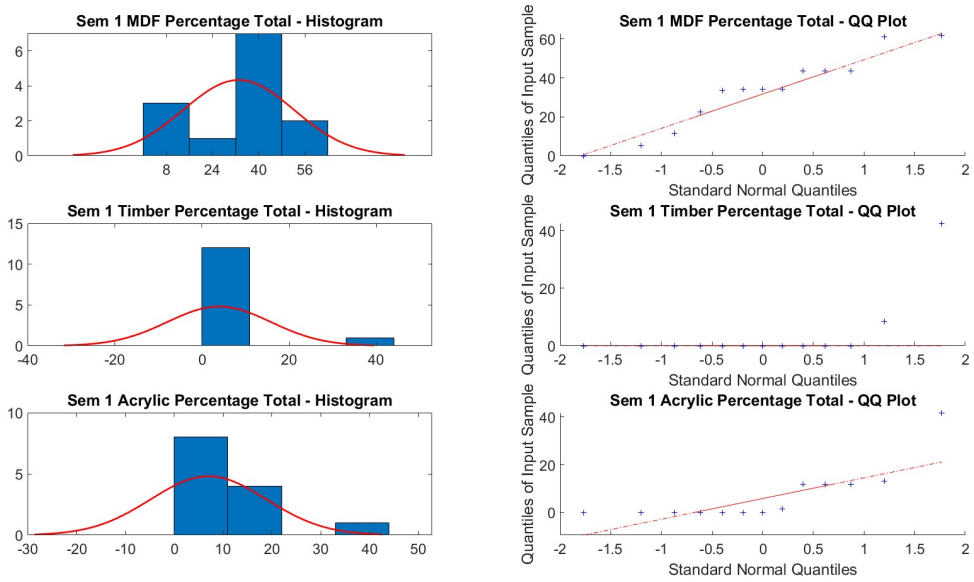


Figure 17: Histogram and QQ Plot of Moving MDF Timber Acrylic Proportion Semester 1

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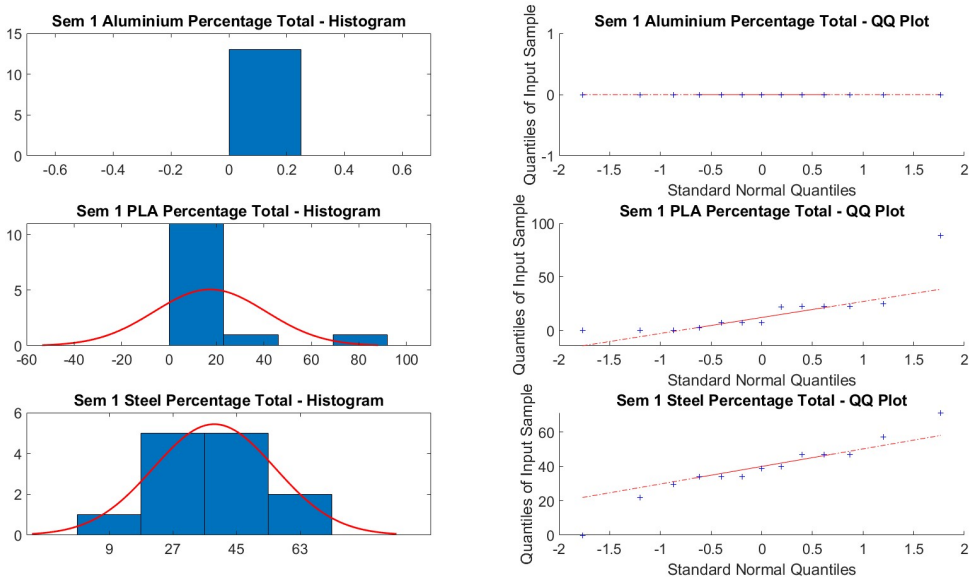


Figure 18: Histogram and QQ Plot of Moving PLA Aluminium Steel Proportion Semester 1

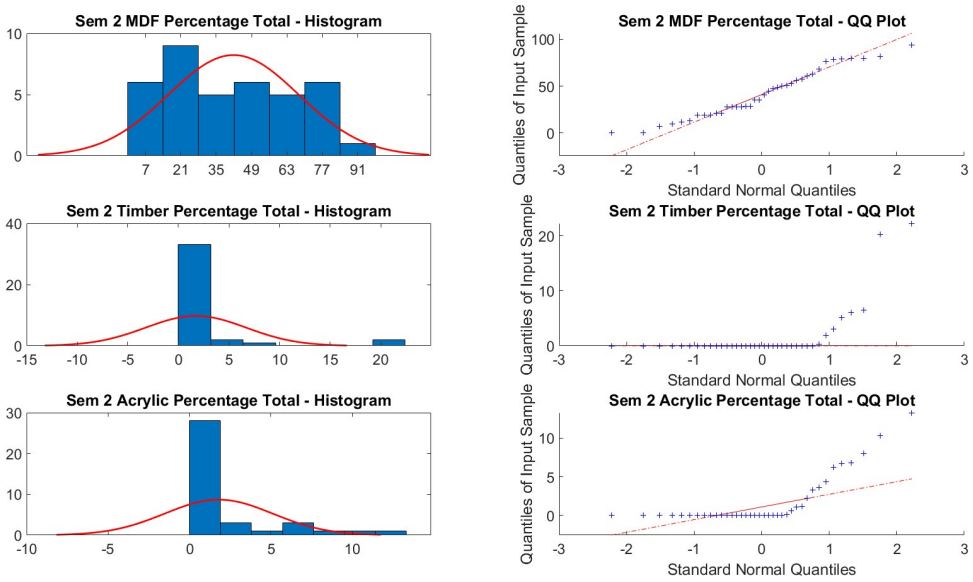


Figure 19: Histogram and QQ Plot of Moving MDF Timber Acrylic Proportion Semester 2

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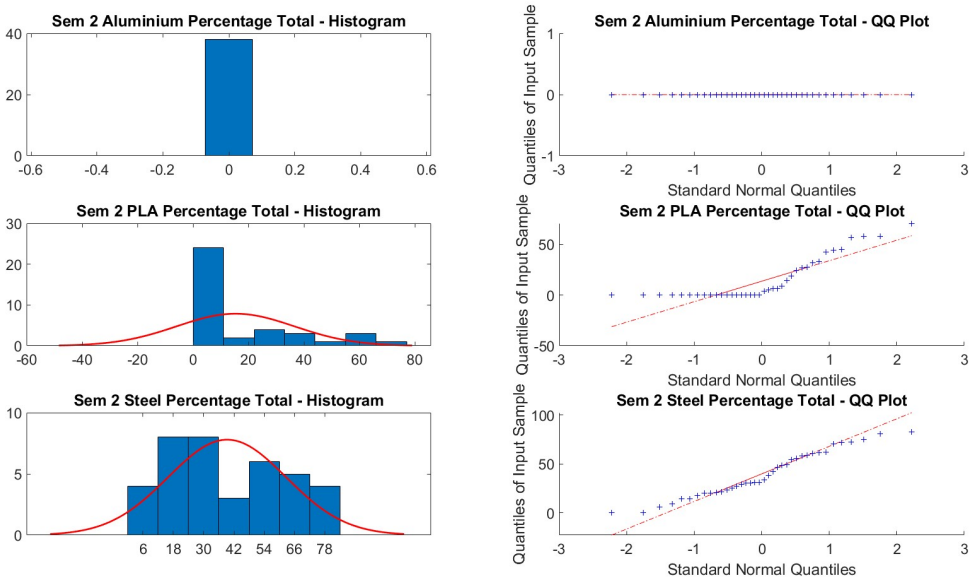


Figure 20: Histogram and QQ Plot of Moving PLA Aluminium Steel Proportion Semester 2

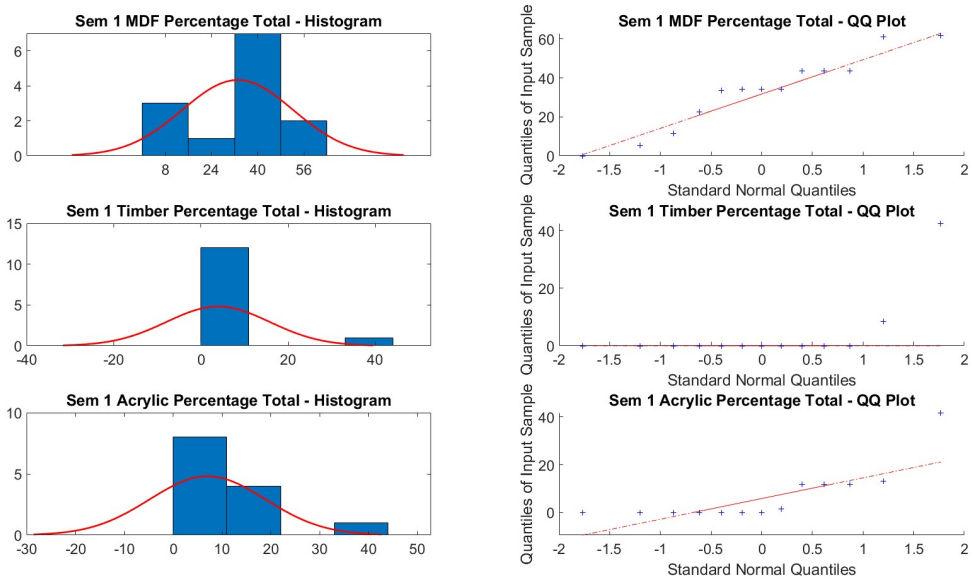


Figure 21: Moving MDF Timber Acrylic Proportion Semester 1

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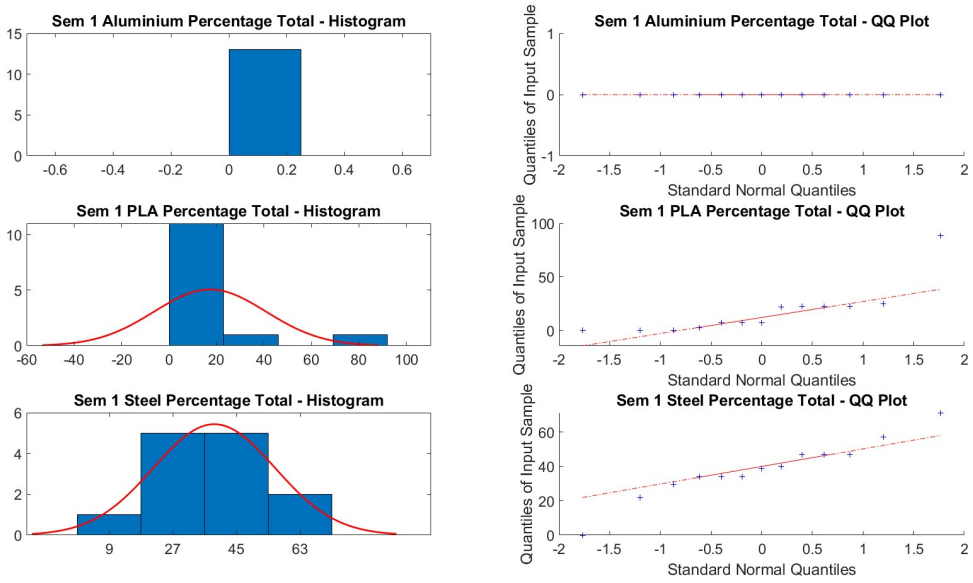


Figure 22: Moving PLA Aluminium Steel Proportion Semester 1

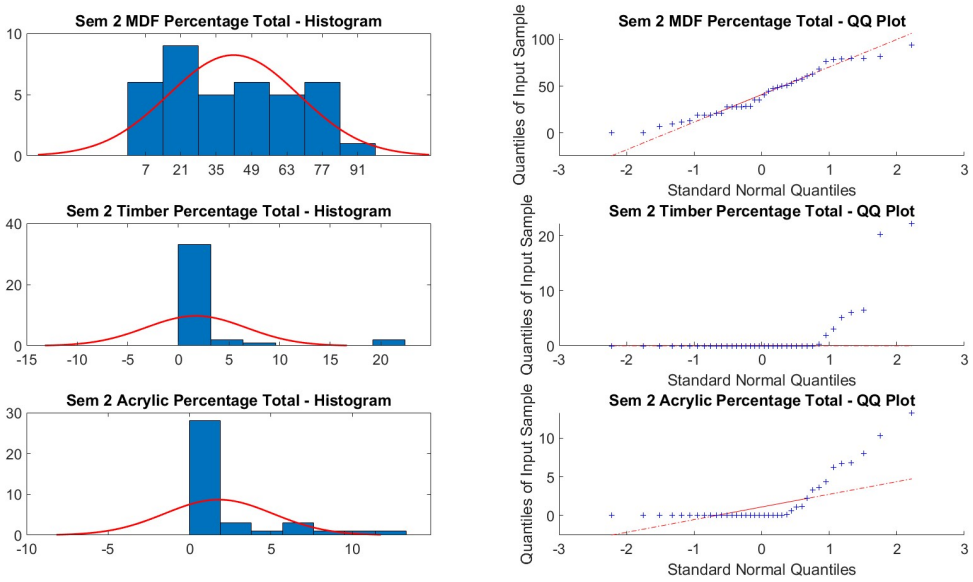


Figure 23: Moving MDF Timber Acrylic Proportion Semester 2

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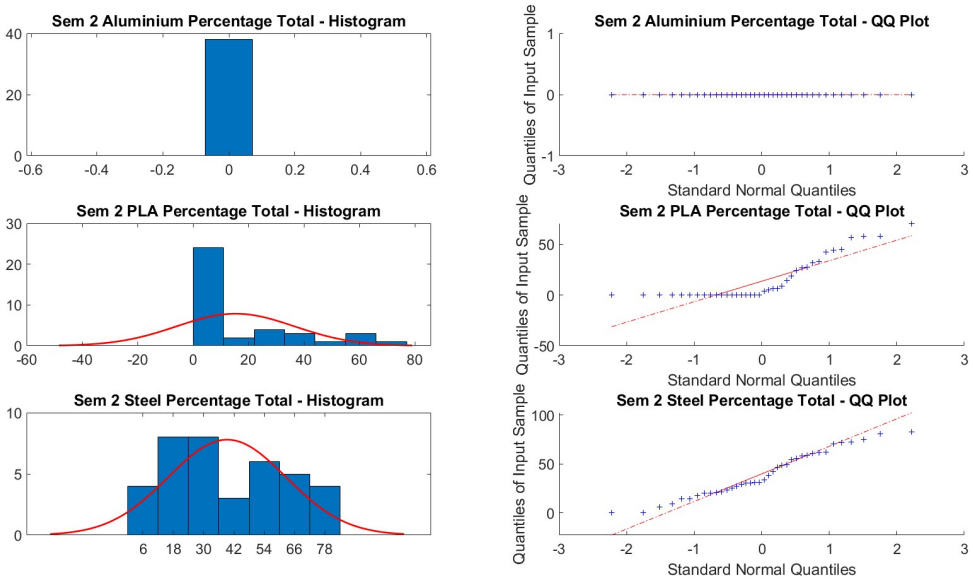


Figure 24: Moving PLA Aluminium Steel Proportion Semester 2

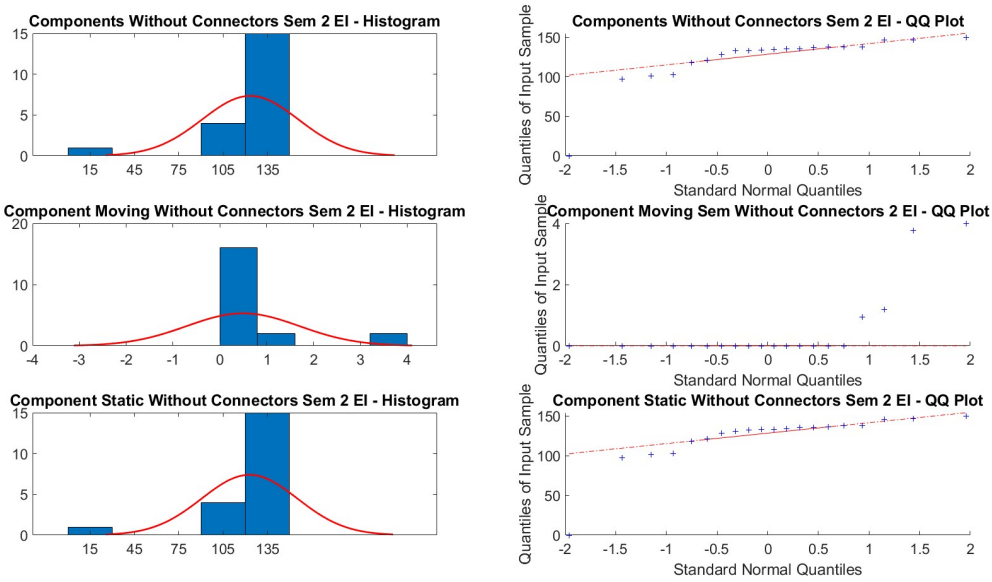


Figure 25: Histogram and QQ Plot of Project Components Without Connectors Semester 2

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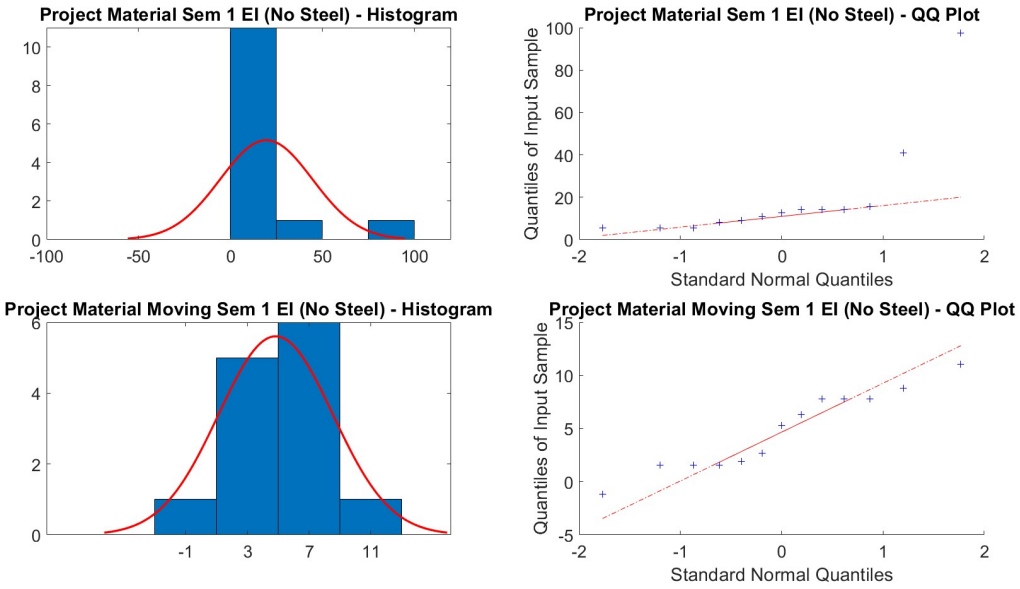


Figure 26: Histogram and QQ Plot of Project Materials Without Steel Shafts Semester 1

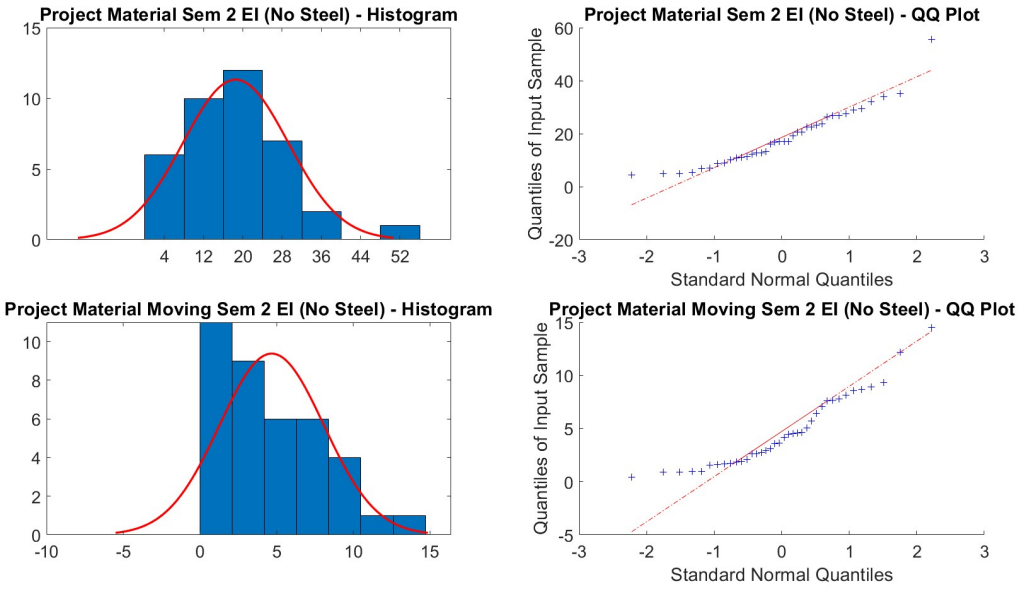


Figure 27: Histogram and QQ Plot of Project Materials Without Steel Shafts Semester 2

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Appendix: Boxplots

Boxplots of Average Project Material and Component Environmental Impact (EI)

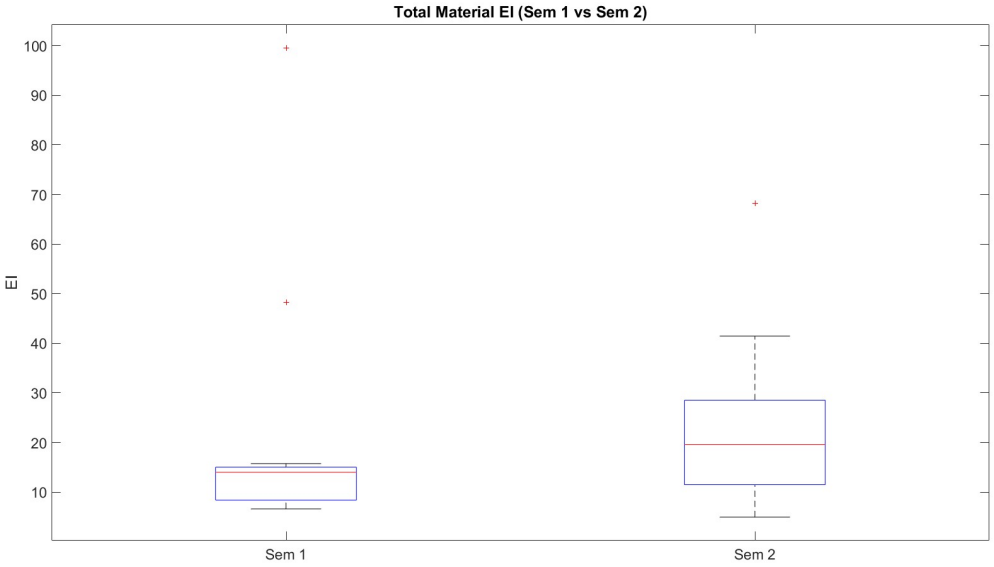


Figure 28: Boxplot of Average Project Material EI

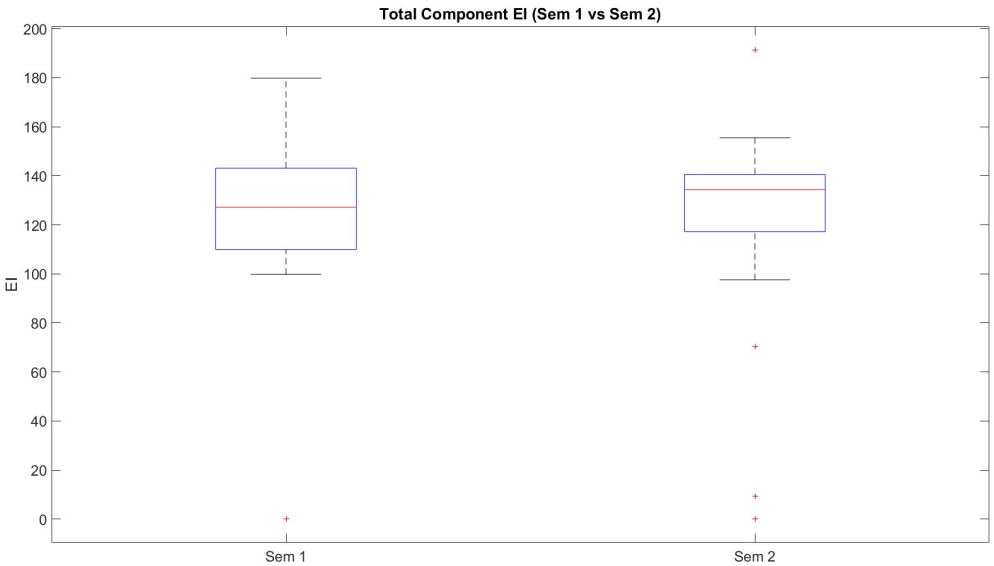


Figure 29: Boxplot of Average Project Component EI

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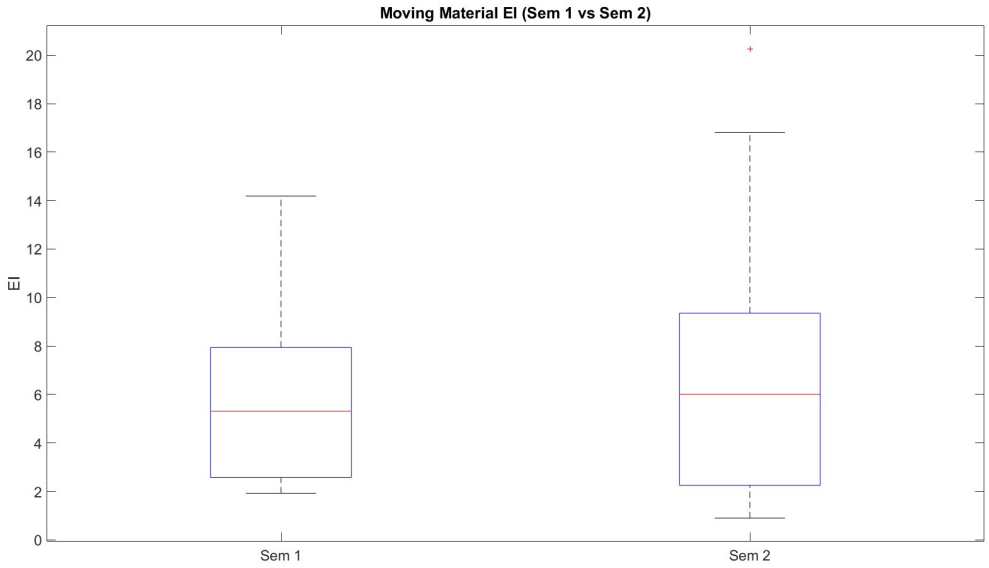


Figure 30: Boxplot of Average Project Moving Material EI

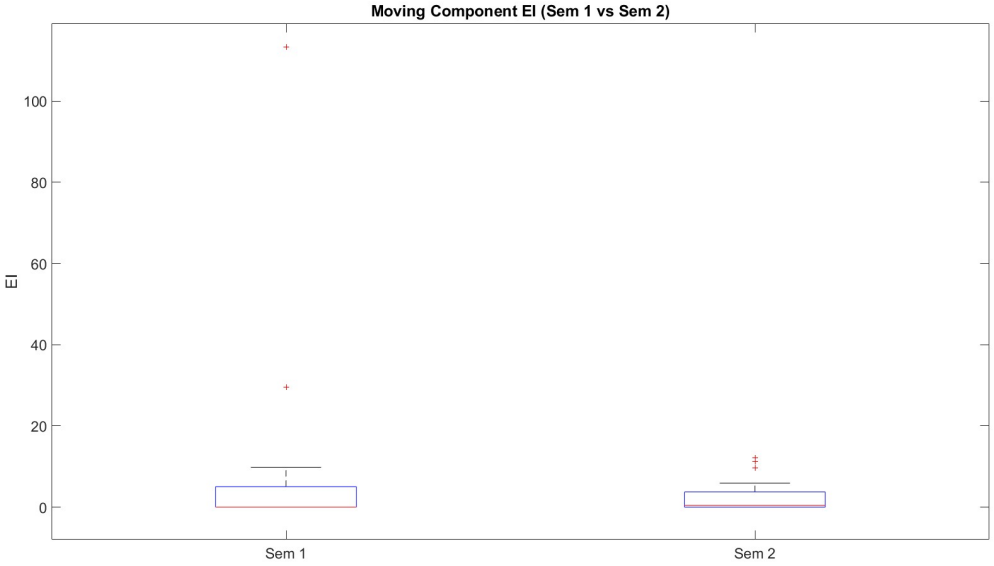


Figure 31: Boxplot of Average Project Moving Component EI

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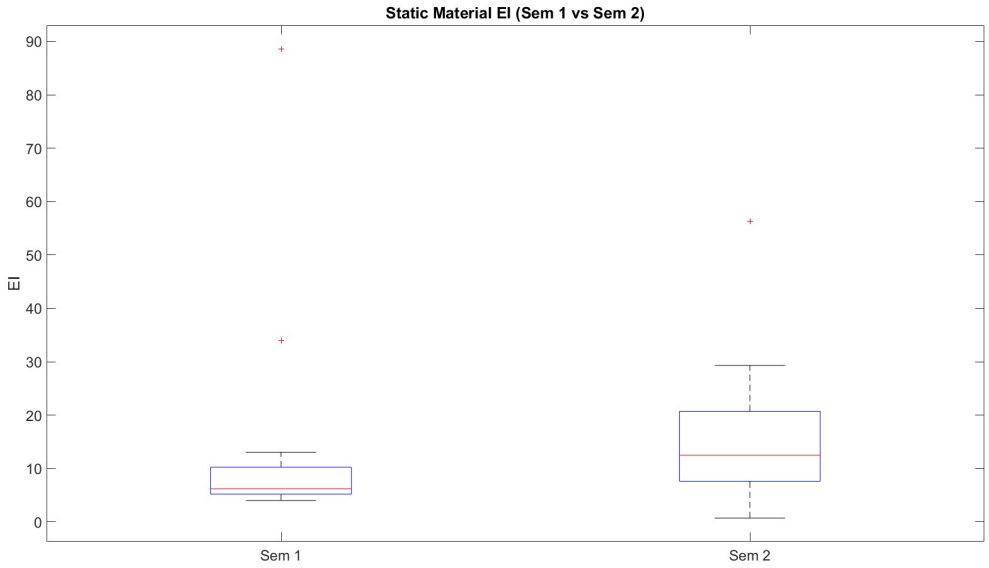


Figure 32: Boxplot of Average Project Static Material EI

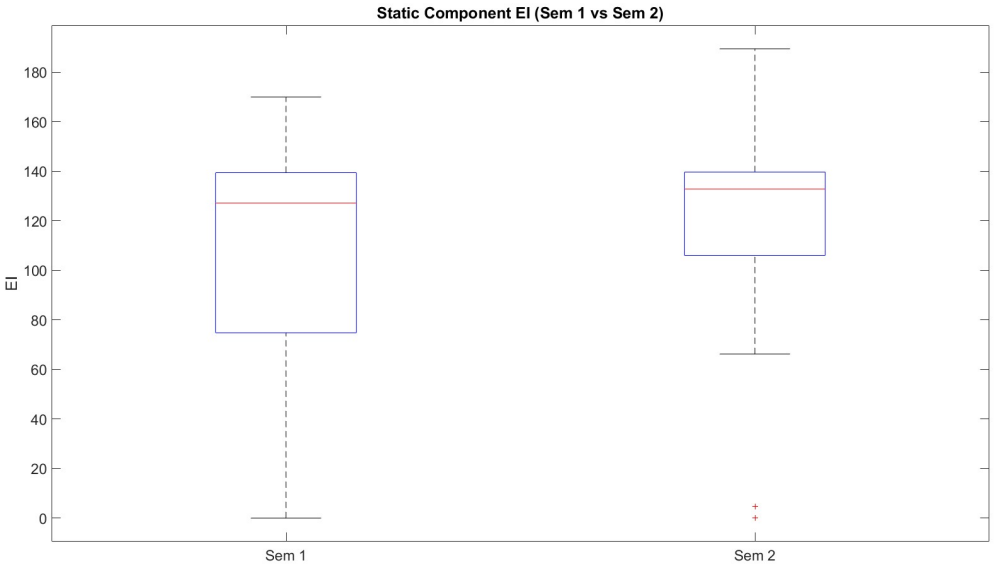


Figure 33: Boxplot of Average Project Static Component EI

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Boxplots of Material EI Distribution as Moving Elements

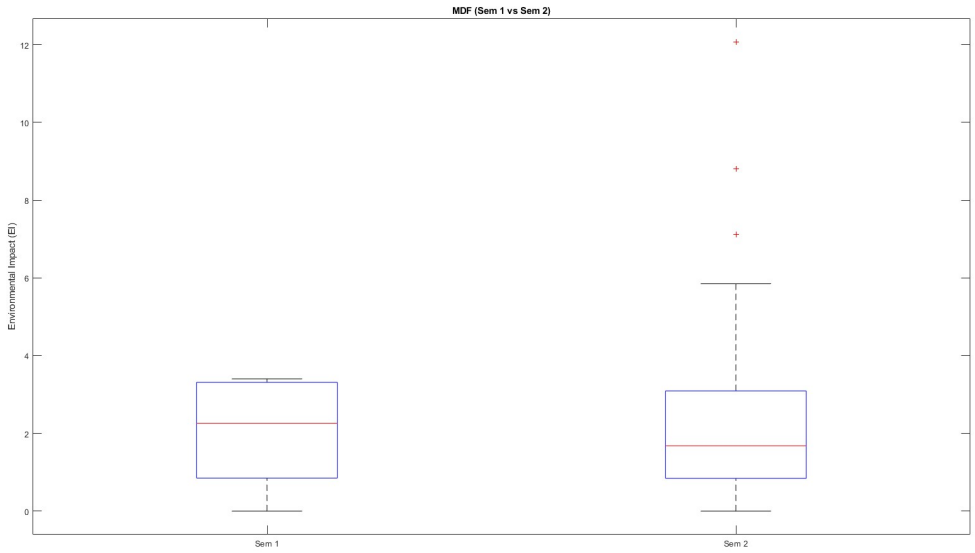


Figure 34: Boxplot of Average Moving MDF EI Across Projects

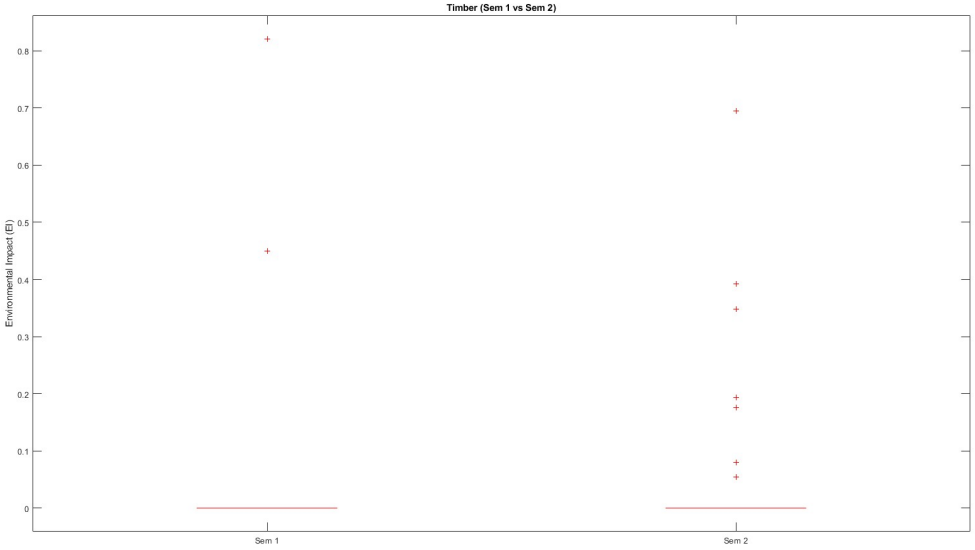


Figure 35: Boxplot of Average Moving Timber EI Across Projects

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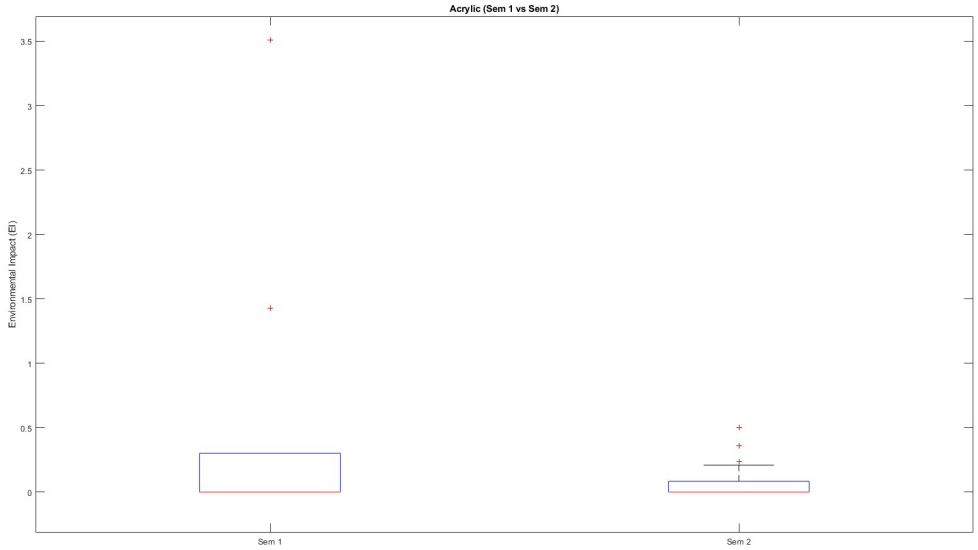


Figure 36: Boxplot of Average Moving Acrylic EI Across Projects

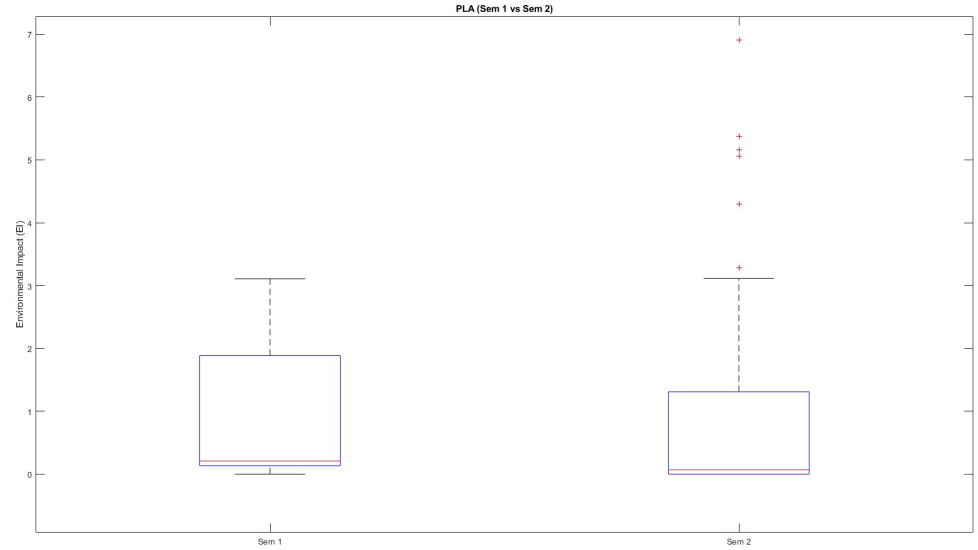


Figure 37: Boxplots of Average Moving PLA EI Across Projects

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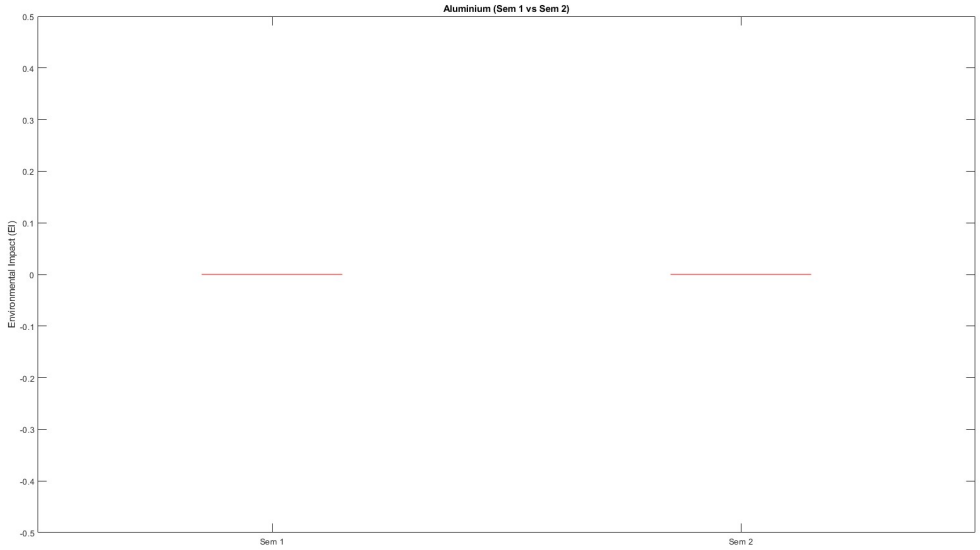


Figure 38: Boxplot of Average Moving Aluminium EI Across Projects

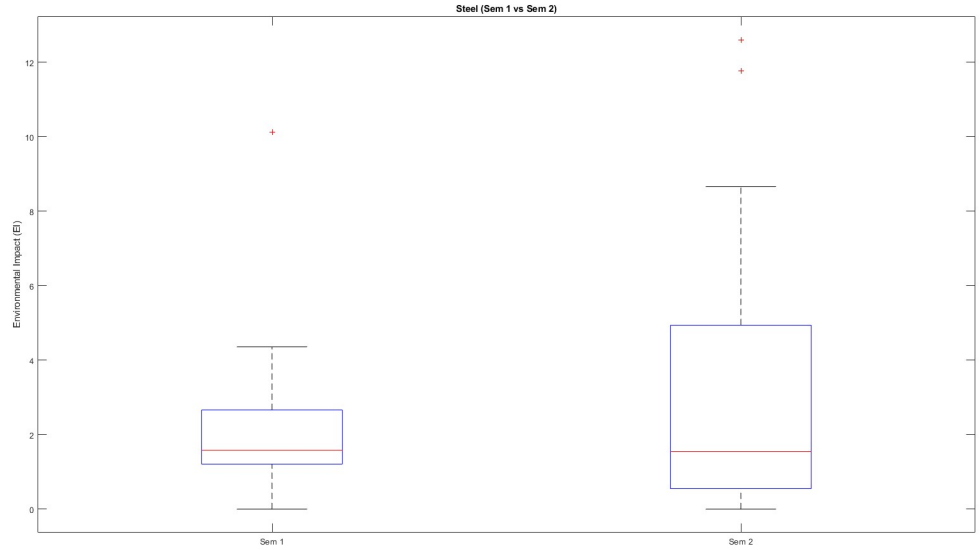


Figure 39: Boxplot of Average Moving Steel EI Across Projects

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Boxplots of Percentage Distribution as Moving Elements

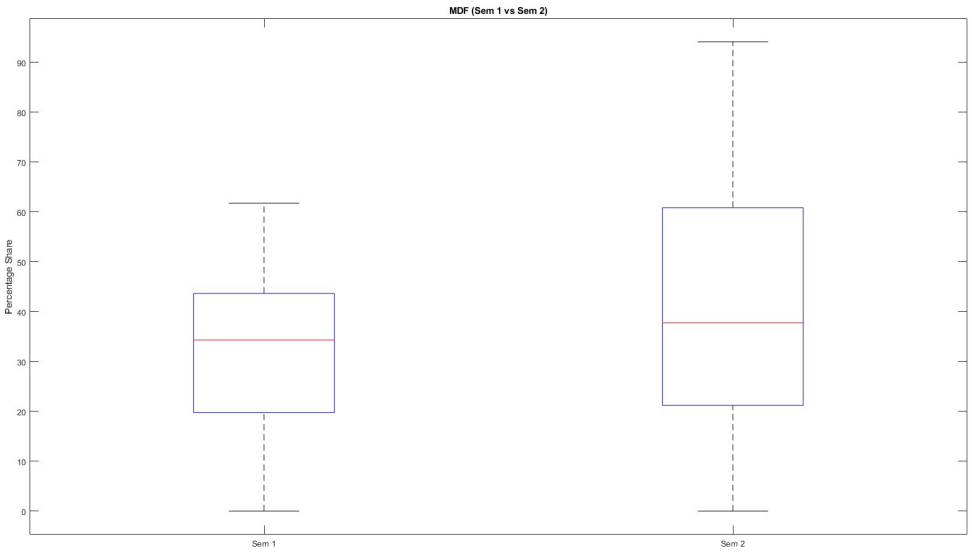


Figure 40: Boxplot of Average Moving MDF Percentage Proportion Across Projects

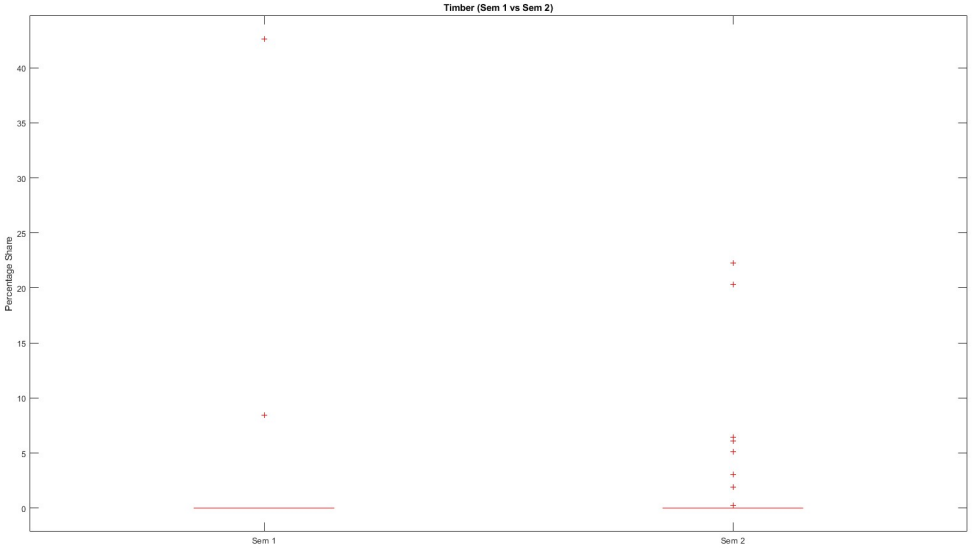


Figure 41: Boxplot of Average Moving Timber Percentage Proportion Across Projects

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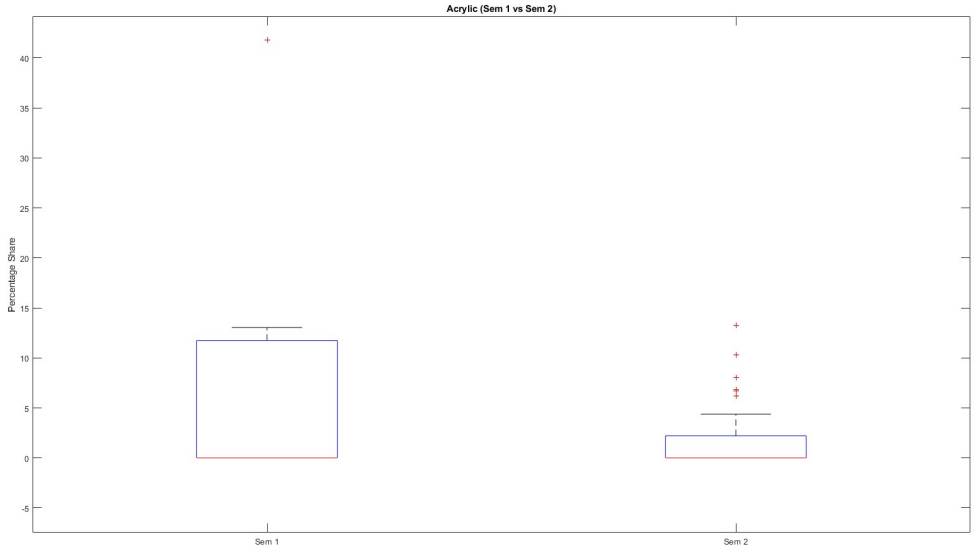


Figure 42: Boxplot of Average Moving Acrylic Percentage Proportion Across Projects

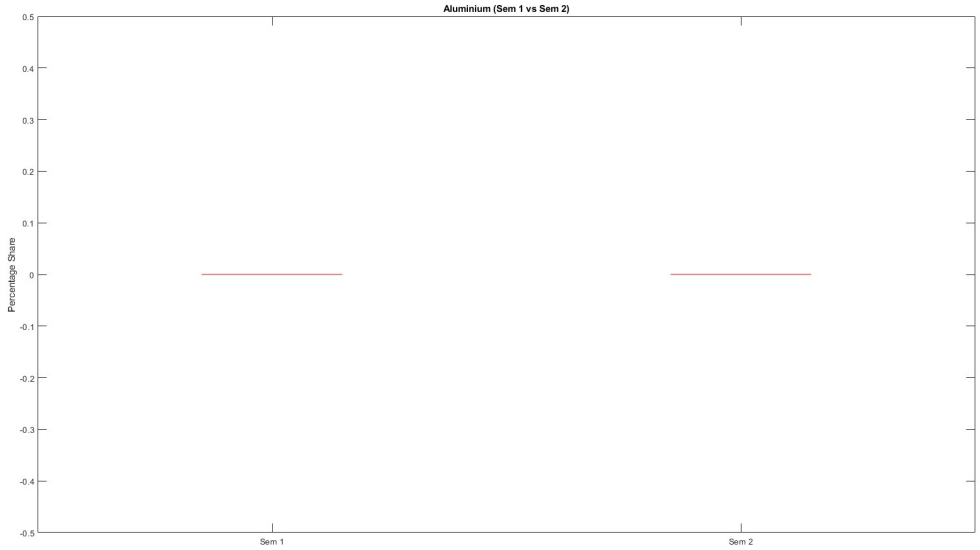


Figure 43: Boxplot of Average Moving Aluminium Percentage Proportion Across Projects

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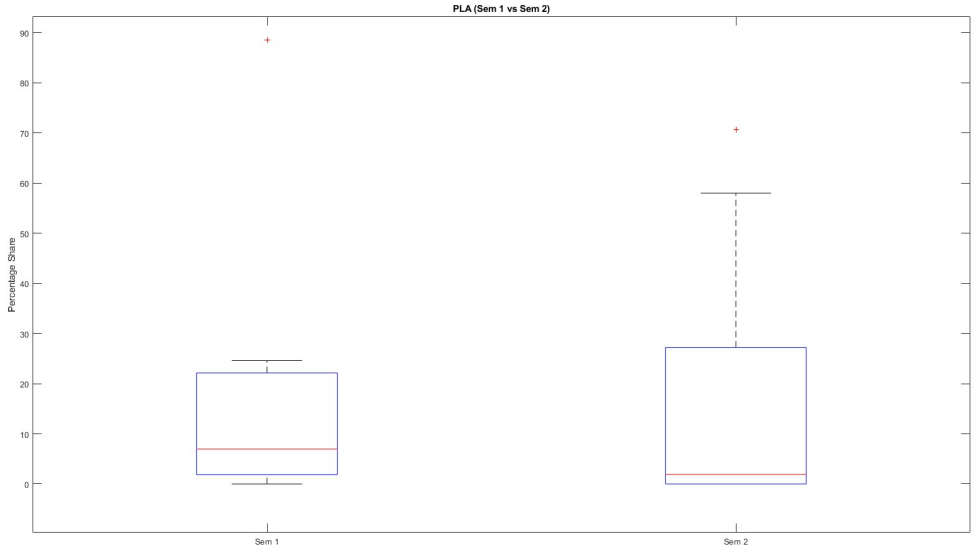


Figure 44: Boxplot of Average Moving PLA Percentage Proportion Across Projects

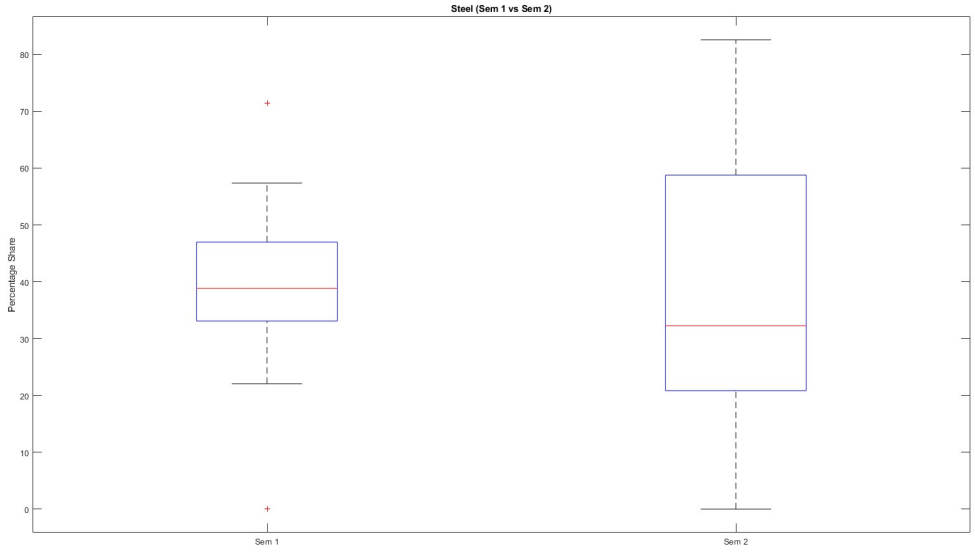


Figure 45: Boxplot of Average Moving Steel Percentage Proportional Across Projects

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Boxplots of Component EI of Projects Without Connectors

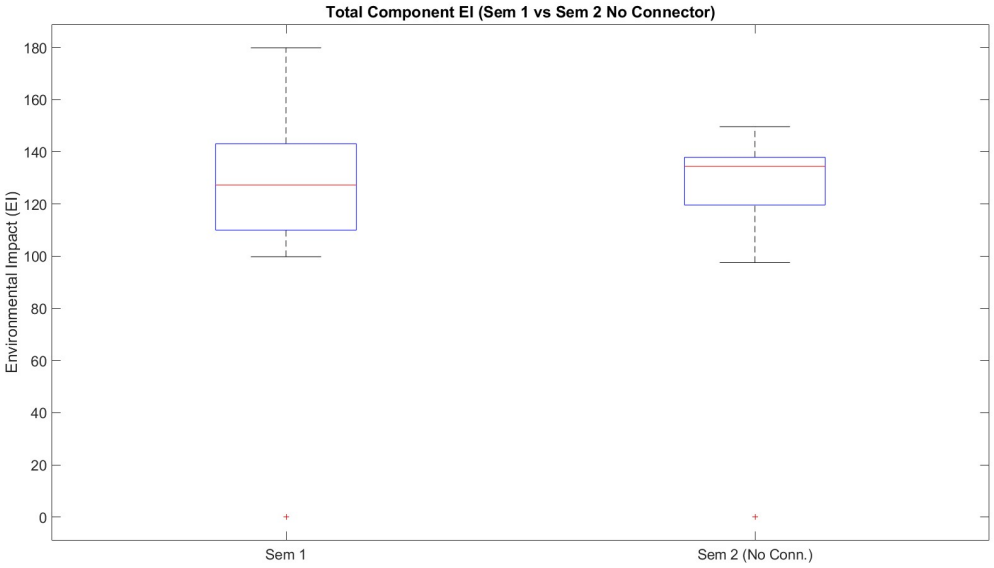


Figure 46: Boxplot of Average Component EI Without Connectors

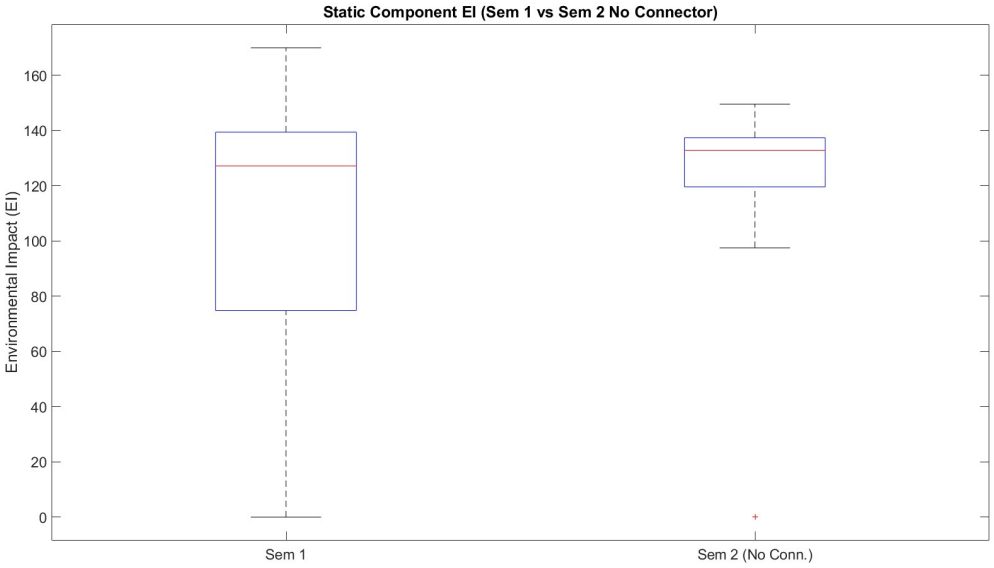


Figure 47: Boxplot of Average Static Component EI Without Connectors

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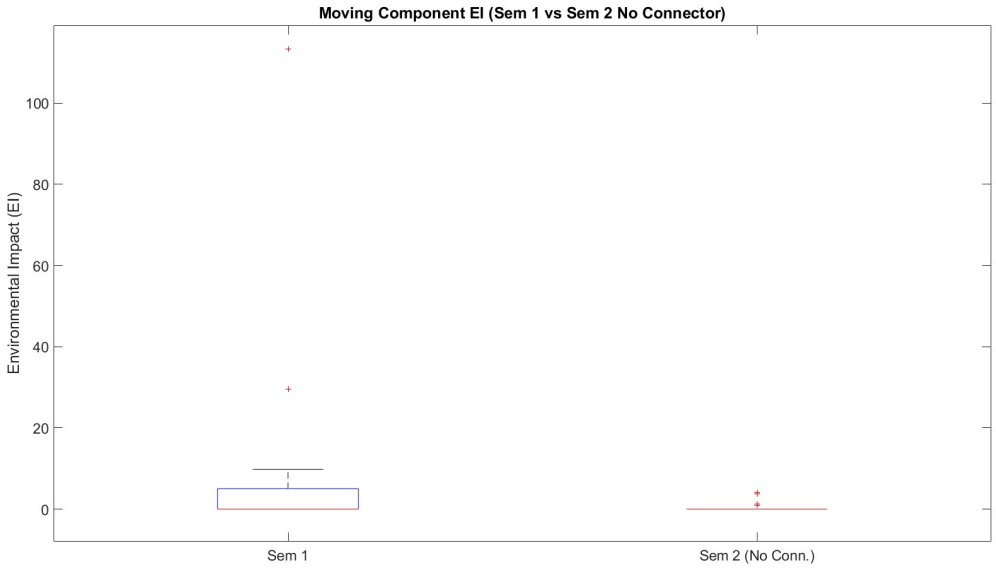


Figure 48: Boxplot of Average Moving Component EI Without Connectors

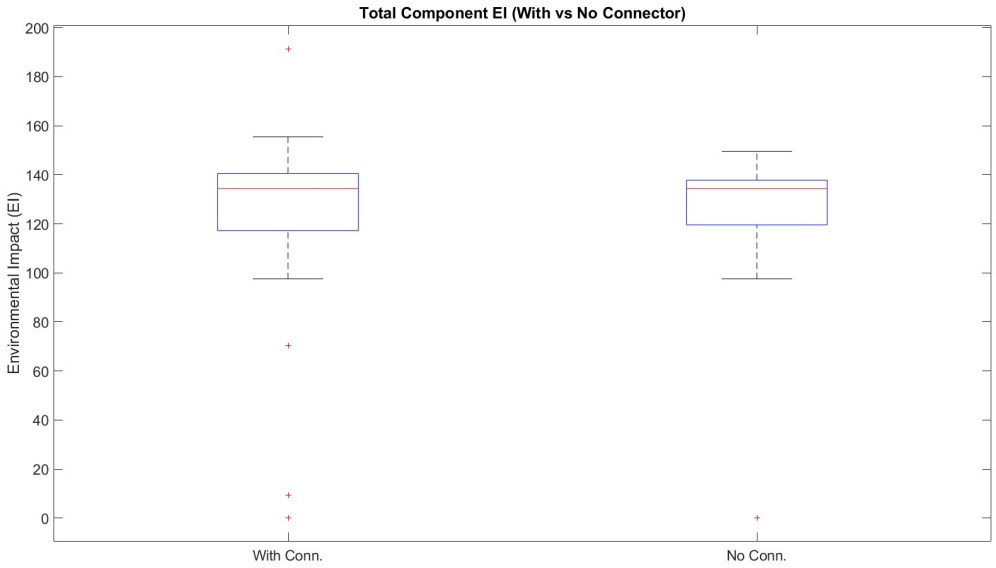


Figure 49: Boxplot of Average Component EI Without vs With Connectors (Semester 2 Only)

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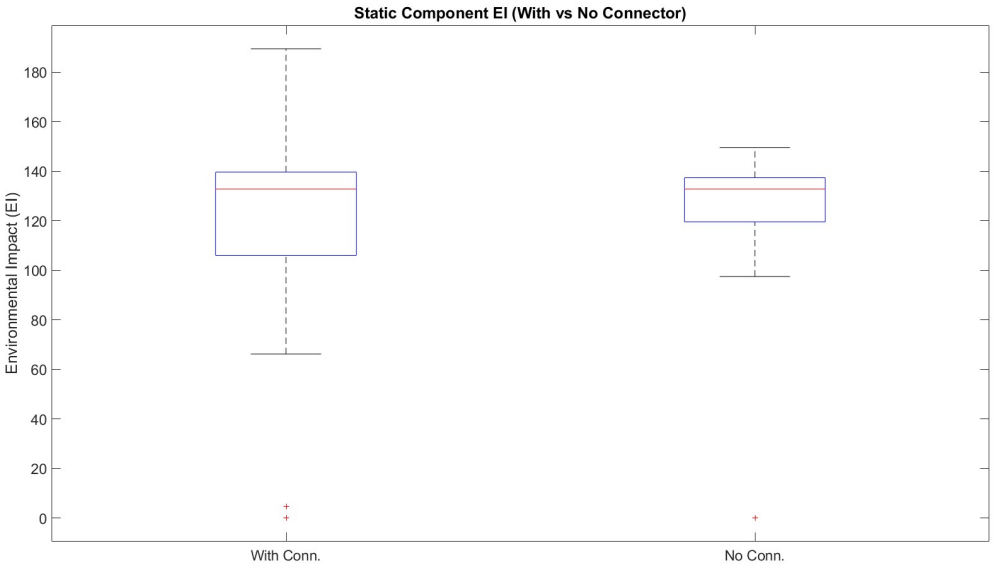


Figure 50: Boxplot of Average Static Component EI Without vs With Connectors (Semester 2 Only)

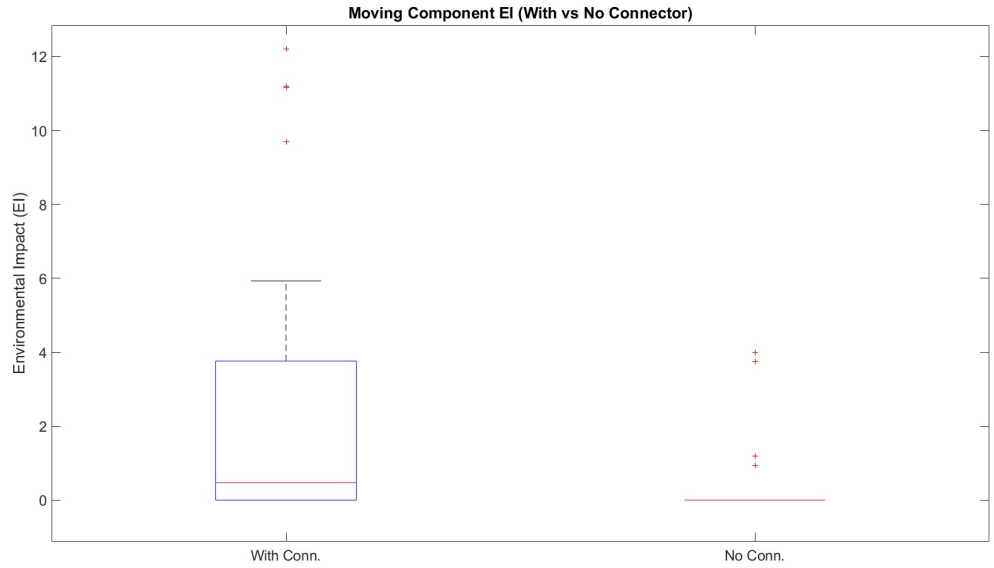


Figure 51: Boxplot of Average Moving Component EI Without vs With Connectors (Semester 2 Only)

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Boxplots of Material EI of Projects Excluding Steel Shafts

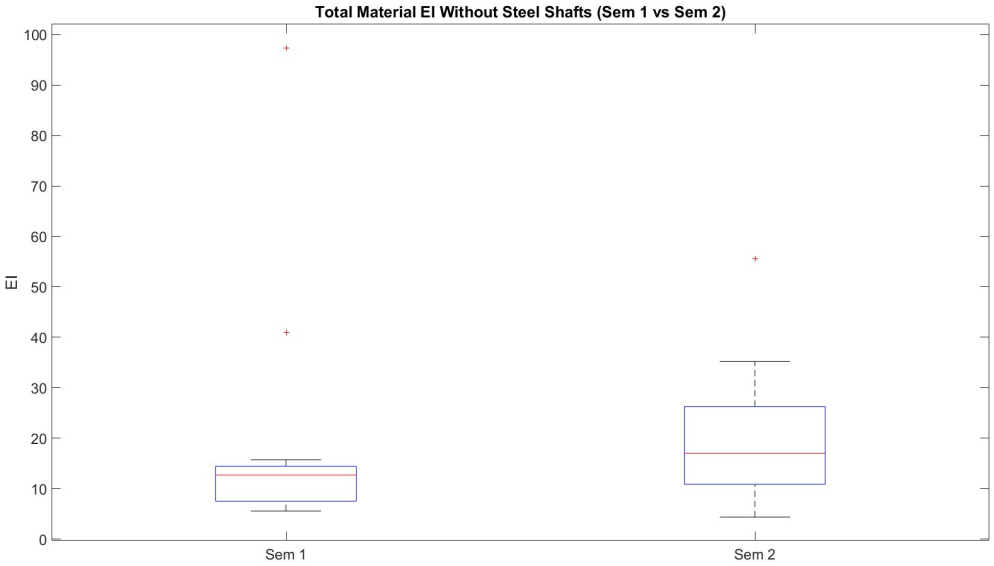


Figure 52: Boxplot of Average Material EI of Projects Excluding Steel Shafts

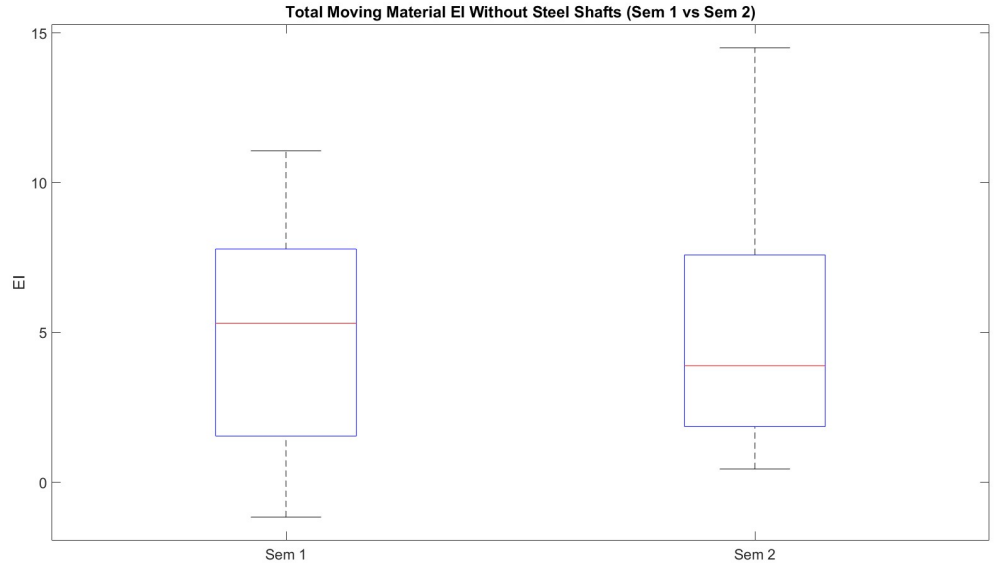


Figure 53: Boxplot of Average Moving Material EI of Projects Excluding Steel Shafts

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