

LEGO Product Design and Manufacturing Simulations for Engineering Design and Systems Engineering Education

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Abstract

This paper describes a hands-on classroom activity to introduce students to engineering design and systems engineering concepts by simulating product design and manufacturing processes using LEGO bricks. Classroom simulations, especially those involving simple physical components, help to engage students and communicate abstract concepts. The proposed simulation platform requires modest one-time capital investment, supports real-time data collection, analysis, and visualization, and can be tailored to suit a variety of educational objectives and audiences ranging from pre-college to professional education. The activity models a three-tier vehicle manufacturing logistics system with suppliers, manufacturers, and customers. A simple software product lifecycle management system implemented using Google Forms and Google Sheets allows participants to record time-stamped events such as purchases or sales using phones, tablets, or laptops. Applications focus on specific topics such as product platforms, commonality, and design for manufacturing where participants experience tradeoffs between speed and quality, standardization and product variety, monotony and specialization, manufacturing learning curves, and how to identify and improve bottlenecks in production lines.

1. Introduction

Systems engineering deals with abstract concepts such as requirements, architecture, design processes, and configuration management. These features make the discipline difficult to communicate to a broad audience, despite providing critical competencies for the design, operation, and sustainment of complex products. Engineering education incorporates some systems-oriented concepts through initiatives such as design and systems thinking [1] and conceiving-designing-implementing-operating [2], both of which emphasize elements of synthesis and taking a systems-level perspective in design applications.

Transitioning design-oriented lessons to short-duration classroom activities is challenging due to long timescales and high costs typically associated with real-world product lifecycles. This paper introduces a series of hands-on classroom activities to introduce participants to systems engineering concepts by simulating product design and manufacturing processes using LEGO bricks. Classroom simulations provide an opportunity for play—“a fun, voluntary activity that often involves make-believe, invention, and innovation” [3]—that encourages participants to immerse themselves in a contextual environment, make decisions in pursuit of objectives, and experiment with the freedom to fail [4].

Applied to systems engineering, classroom simulations, especially those involving physical artifacts, engage participants and help communicate abstract concepts common in engineering, product design, manufacturing, and management. Activities also benefit from real-time data collection, analysis, and visualization using online platforms to strengthen the connection between educational objectives and activities. LEGO brick-based simulations require modest capital investment and can be tailored to suit a variety of educational objectives and audiences.

This paper describes two such activities developed by the authors over the past 10 years for groups of 15 to 60 participants ranging from pre-college to professional education.

2. Background

There is a long history of applying simulations and games for educational purposes [5] including a reemergence over the past decade coinciding with increasing access to digital and online media [6]. Part of the educational philosophy behind simulations and games builds on a constructivist theory that participants create knowledge through action [7]. Games provide a simulated environment for a participant to experience a problem, test solution strategies, and learn about their effects in a feedback loop. Other main drivers behind game design include storytelling, game balance, and directing participants' cognitive load towards learning objectives [8].

Designing games for educational purposes is difficult due to numerous competing dimensions. Harteveld [9] describes the triadic design principles of reality, meaning, and play. Reality captures the relationship between the game world and the real world. Meaning highlights the purpose of a game to meet learning objectives. Finally, play helps engage participants within an activity by providing enjoyment and fun. Although digital platforms provide an opportunity to increase realism of learning environments, they may do so at the cost of meaning (confusing or losing sight of the key learning objective) or play (losing engagement and enjoyment through over-complicated interfaces or activities). Some researchers have recently returned to low-tech physical games to help focus research games on the most important issues [10].

In specific domains such as management and supply chain logistics, well-known classroom activities such as the Beer Distribution Game started using highly-simplified physical forms to emphasize the key learning objectives [11]. Later computerization considerably reduces the time required to play without losing key learning objectives [12]. This perspective uses physical simulations to focus on key learning objectives with technology support to mediate time-consuming (but not value-added) activities such as record-keeping.

In the engineering domain, LEGO bricks are a dominant form of classroom activities in pre-college programs focusing on robotics [13]. In systems engineering, LEGO bricks have most commonly been applied to teach lean principles [14]. In particular, the work of McManus et al. [15] has been influential to structure the activity discussed herein. The remainder of this paper focuses on how similar LEGO brick-based simulations can be adapted to multiple learning applications and how technology platforms can support some of the data collection and analysis without disrupting the core physical activity of building and managing LEGO brick vehicles.

3. Simulation Platform

This section introduces a LEGO brick-based simulation as a general-purpose platform extensible to a variety of application cases. This section provides a brief overview of the proposed platform, introduces necessary physical and software components, and describes a typical game session.

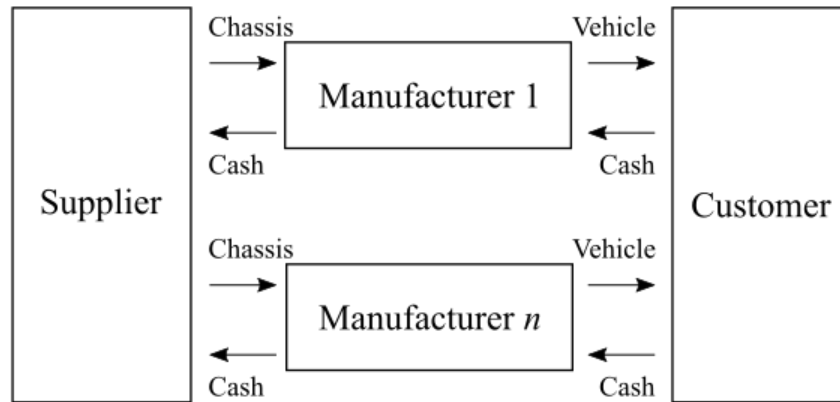


Figure 1. The three-tier logistics system includes suppliers, manufacturers, and customers.

3.1 Platform Overview

The simulation activities model a three-tier manufacturing logistics system in Figure 1 where student manufacturing teams purchase raw materials from a supplier, assemble LEGO brick vehicles, and sell completed vehicles to customers subject to a time constraint. The supplier role is more passive than other roles and can be fulfilled by support staff (i.e. teaching assistants) or volunteers. In the case of teams larger than seven or eight members, some participants can be delegated to supplier and customer roles; however, it is recommended to mix members across teams to avoid conflicts of interest and to rotate roles in between game rounds. Each manufacturing teams includes four to eight team members who self-organize into specific roles such as task-specific workers, runners to purchase/sell chassis or vehicles, quality control, etc. One participant per team serves as a customer for other teams to incentivize truthful quality inspection when purchasing completed vehicles.

Each team starts with a fixed amount of money at the start of a round and must remain cash positive which presents a challenge to carefully manage cash flow while maximizing production. Play money helps to enforce the financial constraints. Teams compete to have the highest amount of cash on hand at the end of a round, typically timed to about 20-30 minutes, with no residual value for unsold inventory. Vehicles intended to be sold must identically match a master or blueprint provided to each team at the start of a round. The customer can reject a sale for any quality defects such as missing components, misplaced components, or incompletely attached components. The penalty for non-quality should be quite large as it reflects warranty costs in the real world which can be very significant [16]. Quality defects can lead either to confiscation, financial penalty, or return of the vehicle to the manufacturer for warranty service.

3.2 Physical Components: LEGO Brick Vehicles

Vehicles require about 20-40 individual LEGO brick parts and 1-2 person minutes to assemble. For example, the vehicle in Figure 2 requires 25 parts (16 unique) which model the undercarriage (one 4x6 chassis, two 1x4 plates with bearings, and four 8x9mm wheels with 14x9mm tires), front bumper (one 1x2-1x2 bracket with two 1x1 tiles for lights), rear bumper (one 1x2-1x4 bracket with two 1x1 tiles for lights and a 1x2 tile for a license plate), interior (steering wheel

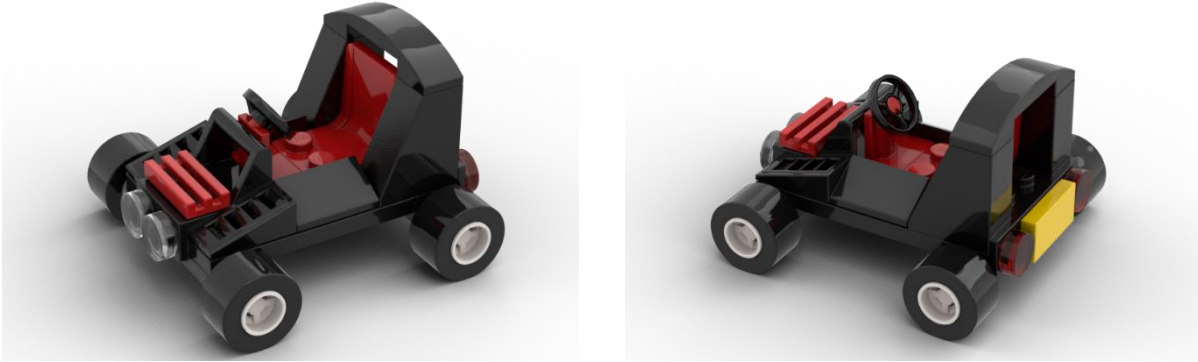


Figure 2. Example LEGO brick vehicle requiring 25 parts (16 unique).

and seat), and exterior structure (one 1x2 tile for a vent, one 1x2 handle for a windshield, two 2x1x2/3 slopes for fenders, two 1x2x2/3 slopes for doors, two 2x1x2 slopes for side panels, and a 4x1 curved slope for a roof). Freely available LEGO brick CAD modeling tools such as BrickLink Studio [17] generate high-quality renderings shown in this paper, collect supporting information such as bills of material (BOMs), and link to online marketplaces.

When designing a class of vehicles, note that specific part availability (including colors) is highly variable for large or bulk purchases and maximum order quantities are limited to 999 units via the online LEGO Pick a Brick store. Furthermore, participants generally do not have any issues with creative interpretation of LEGO pieces purchased based solely on availability. When ordering, anticipate each team may produce up to 50 vehicles during a 20-minute period or about 80 vehicles during a 30-minute period and adjust the purchase quantity with a 25% margin due to imbalanced parts. For example, to support four concurrent teams in a 20-minute session, order 250 single-use items (chassis plates, steering wheels, etc.), 500 two-use items (bearing plates, slopes for fenders and external structure, tiles for lights, brackets for bumpers, etc.), and 999 four-use items (wheels, tires, seats, etc.). Supporting four concurrent teams (around 30 total participants) can cost around \$2000 using the LEGO Pick a Brick online store and lower cost options may be available through volume-based Pick a Brick at physical LEGO Store locations and through third party marketplaces such as BrickLink.

To limit process complexity in the activity, suppliers only control vehicle chassis (typically 4x6, 4x8, or 4x10 plates) and manufacturers control all other parts (wheels, tiles, plates, etc.) in excess. An initial inventory of non-chassis parts is provided to manufacturers upfront. A unique identifier or ID (e.g. A103 or B241 where the prefix letter identifies the chassis type such as 4x6 or 4x8 plate) printed on a sticker and affixed to the bottom of each chassis allows electronic tracking during the manufacturing process. Food-quality plastic containers in a variety of sizes ranging from small 2 oz. (for small tiles) and 8 oz. (for small bricks) to large 32 oz. (for numerous/bulky components such as tires/wheels and chairs) work well for storage.

3.3 Software Components: Product Lifecycle Management System

In addition to the physical supplies, the simulation activity uses a simple product lifecycle management (PLM) software system implemented using Google Forms and Google Sheets to

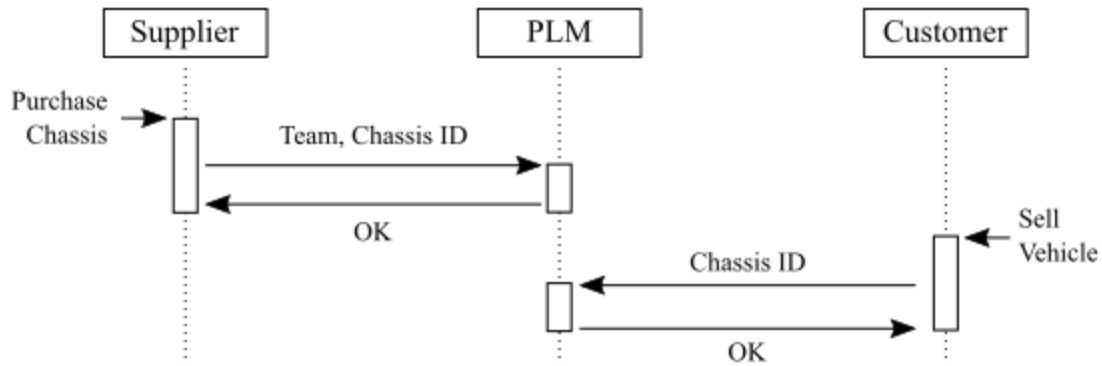


Figure 3. Sequence diagram showing interactions between supplier form, customer form, and PLM sheet.

Round 2 Results			Time Left: 0:00:00		2018 Hall of Fame	
Team	Type	Revenue	In Progress	Completed	Cash	
Red Emmit	A	\$104	n/a	A002, A014, A018, A043, A046, A062, A063, A064, A072, A073, A094, A103, A104, A108, A128, A129, A153, A155, A161, A164, A174, A177, A188, A197, A200, A202, A209, A220, A222, A225, A226, A237, A244	\$2,542	1 Red Emmit \$2,542
Orange Black	A	\$104	A026, A183, A215	A013, A015, A032, A036, A055, A074, A079, A087, A089, A092, A098, A132, A144, A145, A154, A160, A170, A171, A182, A184, A196, A203, A211, A221, A223, A230, A238, A245	\$2,082	3 Green Envy Lantern \$2,170
Green Envy Lantern	A	\$104	A001, A040, A078, A224, A241	A004, A007, A012, A016, A017, A021, A027, A038, A041, A047, A075, A076, A095, A099, A105, A110, A112, A116, A126, A150, A156, A158, A175, A186, A187, A201, A210, A214, A229, A242	\$2,170	4 Orange Citrus \$2,098
Blue Nonames	A	\$104	n/a	n/a	\$100	5 Orange Black \$2,082

Figure 4. Example PLM dashboard showing near real-time information during a simulation.

record and analyze data from a game session provided a reasonably high bandwidth internet connection is available through wireless or cellular networks. A version of the PLM application is publicly available to copy from the authors online [18]. This PLM platform builds on familiar spreadsheet software and equations to post-process and visualize results in a web-accessible format compatible with a variety of bring-your-own devices including phones, tablets, or laptops.

Google Forms allows participants to record time-stamped events in a centralized data store. The sequence diagram in Figure 3 shows a typical information exchange between three components: supplier form (for recording chassis purchases), customer form (for recording vehicle sales), and PLM. Forms collect time-stamped information at critical points in time such when a chassis is sold to a manufacturer (submitted by supplier) or when a completed vehicle is sold to a customer (submitted by customer). The form accepts a chassis' unique identifier and any other context-specific information such as the team purchasing the chassis and type of vehicle assembled.

Google Sheets receives form data from all participants, performs post-processing using spreadsheet equations, and visualizes results during a simulation activity. A PLM dashboard in Figure 4 updates in near real-time (updates on form submission or cell edit) during a simulation activity to show important information such as: team names/colors, revenue per vehicle type, chassis IDs in progress, chassis IDs completed, cash on hand, time remaining, and a historical leaderboard. Other visualizations shown after the completion of a round in Figure 5 include a

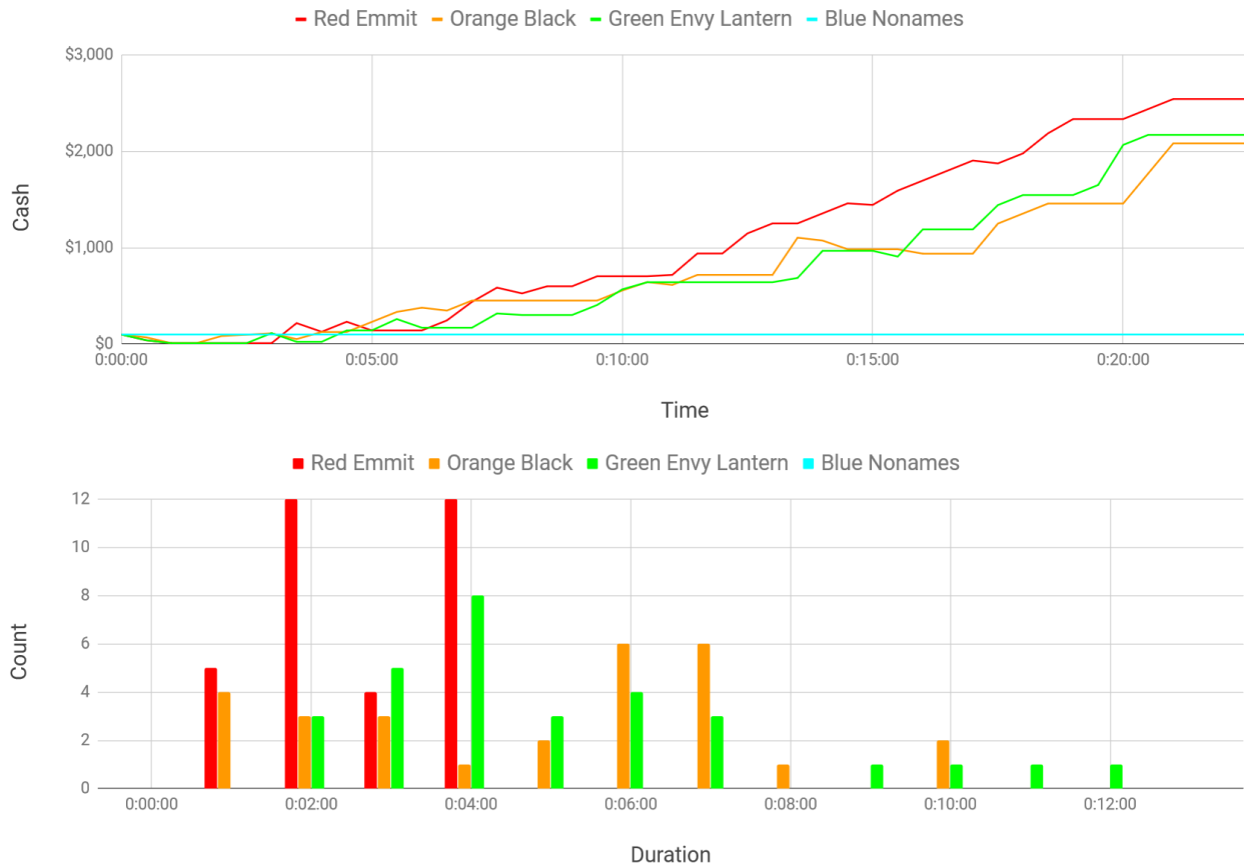


Figure 5. Example plots for cash-on-hand time series (top) and cash-cash duration histogram (bottom).

time series of cash-on-hand, a bar plot of complete versus incomplete vehicles, and a histogram of the cash-cash duration (time from chassis purchase to vehicle sale). This instance shows Team "Red Emmit" emerged as the leader after about 8:00 minutes and maintained a lead until the end.

As in real-life the obtained data is often noisy and must be carefully interpreted to reach valid conclusions. The instructor or support staff should review and manually edit records to remove erroneous data (e.g. incorrect IDs) and append omitted data at the end of a round. For example, the time series in Figure 5 extends beyond the end of the round at 20 minutes to accommodate extended processing of vehicle sales at the end of the round and correcting any missing records.

The example plots in Figure 5 illustrate two common dynamics observed among teams. First, the cash-on-hand time series shows the red team has a more continuous cash flow compared to the green team which has some pronounced waves corresponding to batches of vehicles sold in short succession. A continuous product flow helps to avoid bottlenecks at the customer table but also requires a dedicated "runner" to relay completed vehicles to the customer. Second, the cash-cash duration histogram shows the red team has a narrower distribution of manufacturing durations between 30 seconds and 4 minutes compared to the green team with a wider distribution between 2-12 minutes. This result reinforces the time series data conclusion to explain how the red team exerted control over the production process to achieve the winning score.

3.4 Simulation Game Session

Putting the physical and software simulation components together, a game session includes a series of one or more rounds, each approximately one hour in total duration, with individual sections for introduction, design, build, disassembly, and debriefing. The 20-minute live play session shown in Figure 5 is a subset of the one-hour round.

The introduction addresses background information specific to the learning objectives and explains the roles, rules, objectives, and constraints for the simulation activity. Participants split into teams and pick a unique team name to establish a common identity.

The 10-20-minute design period focuses on the LEGO vehicle(s) to be assembled. Based on the application, teams either review the master/blueprint or create a new vehicle design using support tools such as cost models or customer. In addition to product design, teams also consider process design to identify roles and arrange the workstation or assembly time.

The main body of each simulation round includes a timed period of approximately 20-30 minutes during which teams manage cash flows and produce vehicles. Starting from an empty production queue, the first five or ten minutes are typically cash-constrained and emphasize minimizing the cash-cash time and purchasing as many chassis as possible. After teams enter a steady-state production process, the focus shifts to quality control and managing continuous product flow. Depending on the length of this period, teams may learn and adjust their process and achieve a learning curve effect. Figure 6 shows a clear instance of learning (in this case reflected by two discrete steps to reduce assembly time across three rounds) which can also be visualized using the recorded data and discussed during the debriefing period.

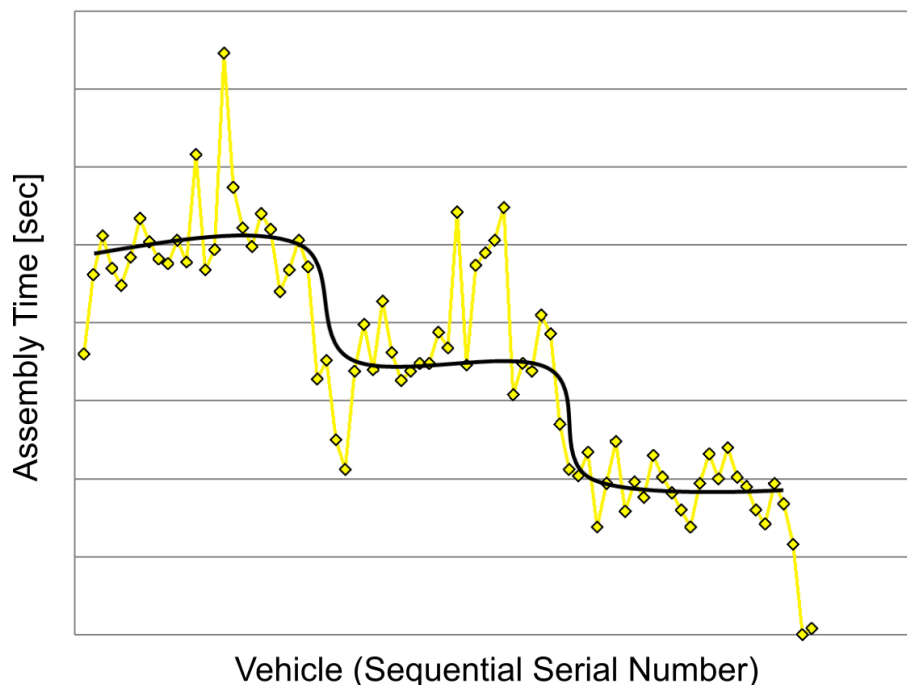


Figure 6. Example scatter plot of assembly duration versus vehicle number illustrating learning curve achieved during LEGO vehicle assembly. Data is noisy as in real-life manufacturing operations.

Towards the end of the time period, teams stop purchasing chassis to minimize the number of incomplete vehicles. To accommodate large selling queues at the end of a simulation, any vehicles on the customer table can be considered complete at the end of the building round.

At the end of the timed round, a 20-minute deconstruction and discussion period allows teams to disassemble completed vehicles and refill component supply stocks. During this time, the instructor can discuss immediate reflections on outcomes with each team and prepare outcome metrics. It can also be helpful to appoint neutral peer observers who report out on the dynamics and strengths and weaknesses. After disassembly is complete, the instructor leads a debriefing session to congratulate the leading teams and discuss the advantages and disadvantages observed by each team as pertaining to the learning objectives. Thorough discussion helps to solidify learning objectives, especially across teams exhibiting different dynamics.

4. Application Cases

This section introduces two applications which build on the simulation platform. The first application is from a short course on product platform and product family design, focusing on issues of commonality in product architectures [19]. The second application is from an introductory industrial and systems engineering module, focusing on the difference between product and process engineering and introducing concepts of design-for-manufacturing.

4.1 Product Platforms and Commonality

This first simulation application focuses on commonality as a design strategy to enable product diversity while maintaining process efficiency of a common platform [20]. The activity nominally proceeds over a series of three or four one-hour rounds.

The first round represents a mass production paradigm where all teams assemble a single baseline vehicle design similar to the "sport" variant in Figure 7. Teams build as many vehicles as possible during the build period. The sale price of a completed vehicle varies in time, monotonically decreasing to a point where it is not profitable by the end of the simulation period. This reflects the effect of commoditization in mass markets [21]. Additionally, quality defects result in an additional financial penalty.

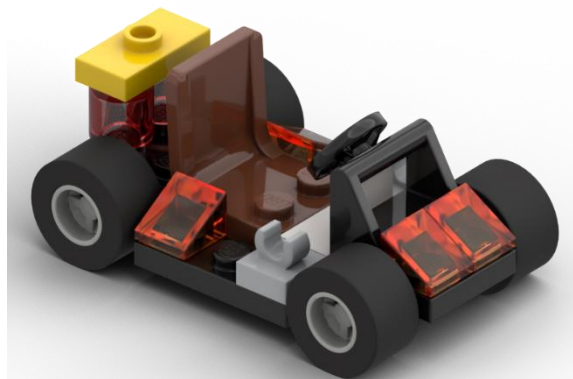


Figure 7. Sport vehicle variant.

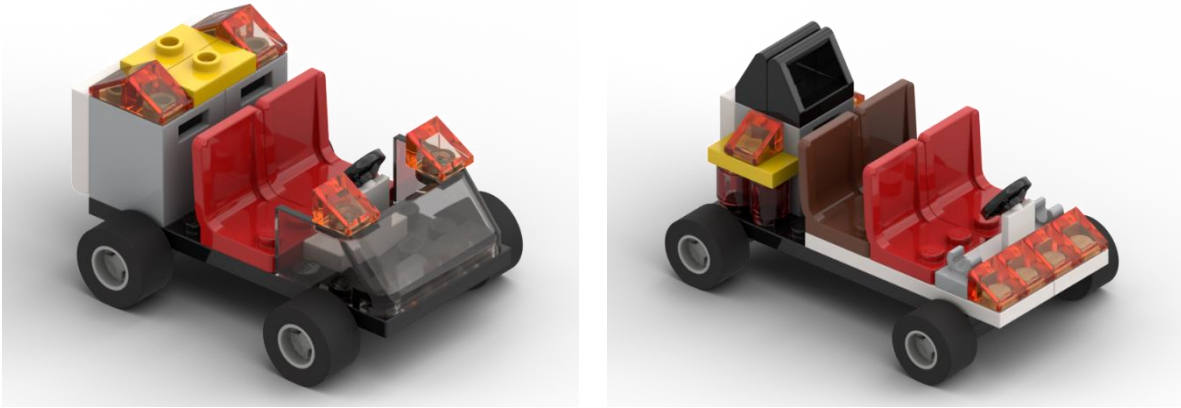


Figure 8. Utility (left) and family (right) variants without intentionally planned commonality.



Figure 9. Redesigned sport, utility, and family variants with a common product platform.

The second round represents a paradigm of production with variety where each team receives two additional product variants similar to the "utility" and "family" variants in Figure 8. A financial reward structure promotes concurrent delivery of all three vehicle types to a customer. The three product variants have no intentionally planned commonality and the addition of new inventory line items and multiple designs poses challenges for production efficiency and quality.

Finally, the third round introduces a mass customization manufacturing paradigm where the three variants are redesigned as a product family with a common product platform. Redesigned variants in Figure 9 all use a common chassis (4x8 plate) and front end to reduce the number of unique components and identify modules common across multiple variants.

Comparing results of rounds one and two typically show a decrease in production efficiency because of the challenge of managing multiple product variants. Production tends to be more chaotic in round two due to the larger product variety, while maintaining constant team size. Comparing results of rounds two and three typically shows a partial recovery in production efficiency due, in part, to the commonality of product platforms. Participants observe the potential benefit of modular architectures and product platforms in managing manufacturing with mass customization. One of the most important concepts taught in round three is the idea of a point of differentiation, downstream of which the assembly line splits from a common trunk to three specialized lines to allow for product variety. A fourth round can be added where participants design their own product platform, subject to product and business constraints.

4.2 Design for Manufacturing

This second simulation application differentiates between process design as the basis for industrial engineering and product design as the basis of systems engineering and introduces design-for-manufacturing as a philosophy to use downstream factors and lifecycle costs to inform upstream design decisions [22]. The activity nominally proceeds over two rounds.

The first round provides teams with a baseline vehicle design in Figure 2. Like the prior application case, teams build as many vehicles as possible during the build period; however, sale prices are fixed for the entire round duration. Teams focus on cashflow management and manufacturing process improvement during the round.

After the first round, teams propose vehicle design changes to reduce manufacturing effort, reduce costs, or increase revenue. To support the design activity, participants use a web-accessible design page hosting a requirements document, cost model, and revenue model to quantitatively compare design concepts. The example interface in Figure 10 shows the set of parts for the default vehicle in Figure 2, indicating it uses the type "A" chassis which costs \$30, meets all requirements, and earns \$104 in net revenue after costs. Participants input design decisions to automatically update estimates of product lifecycle cost used in the following round.

The requirements document presents a set of functional requirements to constrain the design space, largely for safety, similar to the role of a government transportation agency. For example: there must be at least one seat facing forward, at least two clear lights must be visible from the front, at least two red lights must be visible from the rear, and only one chassis may be used. Some requirements may be automatically checked based on a bill of materials (BOM) but others must be visually inspected by the instructor for each proposed design.

The interface displays a summary bar at the top with the following information:

- Chassis: A: \$30
- Req. Met: ☒
- Market Price - Mfg. Cost = Revenue: \$230 - \$126 = \$104

Below the summary bar is a "Parts List" grid with 24 items arranged in 4 rows and 6 columns. Each item is represented by an image of a part and a count field with minus and plus buttons.

Part 1	Part 2	Part 3	Part 4	Part 5	Part 6
Black plate 1x4	Black plate 1x4	Black plate 1x4	Black wheel	White wheel	Black axle
- 1 +	- 0 +	- 0 +	- 4 +	- 4 +	- 2 +
Black axle	Black axle	Red axle	White wheel	Red wheel	Yellow plate
- 1 +	- 1 +	- 1 +	- 2 +	- 2 +	- 1 +
Red wheel	Red wheel	Black wheel	Black wheel	Black wheel	Black wheel
- 1 +	- 1 +	- 0 +	- 0 +	- 2 +	- 1 +
Black plate 1x4	Black plate 1x4	Black plate 1x4	Black plate 1x4	Black plate 1x4	Black plate 1x4
- 0 +	- 2 +	- 2 +	- 0 +	- 1 +	- 0 +

Figure 10. Design model inputs (bill of materials) for the default type A vehicle.

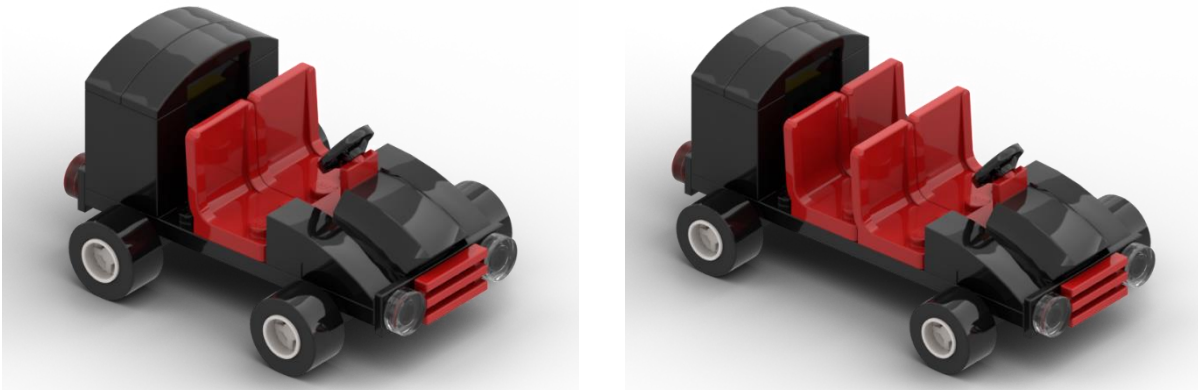


Figure 11. Alternatives using type B (left, \$117 net revenue), and type C chassis (right, \$106 net revenue).

The cost model assigns the cost of supplies based on a BOM. All components are assigned a fixed price loosely based on actual LEGO component price listings. While teams still purchase chassis directly from suppliers, the price of other components is deducted from the sale price to determine the net revenue for a completed vehicle.

Finally, a revenue model computes the gross revenue from selling a vehicle based on seven customer attributes which can be directly estimated from a bill of materials: seating (number of seats), ventilation (number of grill tiles), stability (number of wheels), headlights (number of clear tiles), tail lights (number of red tiles), cargo space (number of blocks typically used as exterior structure), and aerodynamics (number of slope blocks).

Design activities allow participants to search for creative solutions yielding a high revenue or profit. Figure 11 illustrates a two design concepts similar to the baseline design in Figure 2 that increase net revenue by increasing seating and cargo space at the cost of more expensive chassis. The type B vehicle earns \$117 net revenue by adding extra seating, cargo storage, and aerodynamic features. The type C vehicle earns \$106 net revenue by adding even more seating but also requires more costly materials compared to type B, giving a more modest net revenue.

Creative teams can find designs that earn upwards of \$150 net revenue per vehicle; however, the design model does not include any estimate of manufacturing effort and some elaborate vehicle designs require significantly more effort than simple but low net revenue concepts. Many participants' first inclination is to increase revenue per vehicle without considering added manufacturing complexity from an expanded BOM or additional manufacturing steps. Thus, in the second round of production, participants observe tradeoffs in requirements, cost, and value and the effects of product complexity in difficult-to-manufacture designs. The conclusion of round two allows a subtle discussion of revenue, cost, profits as well as integrated design and manufacturing decisions made by each team. Extensions to a third round or beyond would allow teams to iteratively improve their product design and production process to maximize revenue.

5. Conclusion

This paper described a hands-on LEGO brick-based activity to communicate abstract concepts in the area of engineering design and systems engineering. The simulation platform requires a

modest one-time cost for LEGO bricks, storage, online PLM system, and play money supplies which are completely reusable. Lightweight digital components building on common web-accessible spreadsheet-based data management systems such as Google Forms and Google Sheets avoid time-consuming record keeping and post-processing and provide near real-time visual feedback.

Variations of the simulation have been used in pre-college and professional education programs to meet learning objectives in product platforms and commonality and design-for-manufacturing applications. Participants experience tradeoffs between speed and quality, standardization and product variety, monotony and specialization in task assignments, manufacturing learning curves and the need for identifying and improving bottlenecks in manufacturing flow lines. These lessons are highly engaging for participants of all ages and give a firsthand experience with good and bad design decisions without real-world pressures of economic failure or personal losses. Insights reflect on differing design decisions and levels of performance across competing teams.

Although the authors have not formally studied inter-participant dynamics such as role allocation or engagement, framing the activity as an informal competition tends to motivate through peer recognition without requiring any other external incentives. Future work may explore methods to engage specific populations including underrepresented groups and promote equal participation. Other areas of improvement include faster or easier input of chassis unique identifiers (e.g. barcode readers, scanners, or even radio-frequency identification (RFID) chips thus bringing in aspects of industry 4.0 and the internet-of-things), higher fidelity data collection including logging individual manufacturing steps, more detailed automated cost and value models to provide participants with a rich trade space for proposing new designs, and developing new application cases to study new and emerging issues in engineering design and systems engineering. There are also opportunities to extend this activity to consider full system lifecycle properties by formalizing the processes of disassembly and recycling within the scoring of each round. Overall these sets of active learning activities tend to be highly regarded and highly scored during class evaluations, provided they are properly executed and tied in with the deeper more abstract foundational principles.

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