Full Paper

Introduction

Constructionism – a process where knowledge is constructed through manipulation of real- world things – is a natural pedagogical approach for the engineering discipline, where 'making' is a fundamental aspect of professional practice. Yet, the pedagogy behind constructionism (see Papert 1980; Martinez & Stager 2012) is often overlooked in an educational setting, where often there is a clear, convergent and often assessed outcome for any particular session, such as a lab report based on a worksheet.

Distributed constructionism (a term borrowed from Reznick 1996) extends Papert's ideas by putting the design and running of tutorials in the hands of students, building on the concept of student-facilitated learning (see Baker 2008; Smith & Browne 2013). A series of engineering honours projects were created specifically to embed rich hands-on activities that student facilitators could adopt and use in their own tutorial facilitations.

In this paper, we discuss one learning activity designed for a second-year engineering design course. The course has approximately 190 students, and covers introductory systems engineering design principles. The activity, called 'SPOKES', was designed to allow students to discover for themselves the trade-offs process in requirements engineering. The activity was based on a card game, where students in small groups had to make a series of ranking decisions based on a short statement of design requirements for the configuration of a bicycle. The goal of the activity was to configure the bicycle to best meet the customer requirements. Results were collected to establish how well students could make trade-off decisions intuitively. We found that just under half of student groups could achieve an optimal configuration, largely because they make sub-optimal evaluation decision early in the decision-making process.

Mechanics of peer-facilitated tutorials

This activity was trialled during the normal session of a second-year systems engineering course that had previously adopted student-facilitated tutorials as an assessable item of the course. Peer-facilitated tutorials made up 90 minutes of a 2-hour time slot. The peer- facilitated aspect of the tutorial was an extension of course content material; material that had otherwise been presented in seminars, online activities and course reading. Attendance at the tutorials was not required, but tutorials were positioned in the course as the primary point of face-to-face learning in the course.

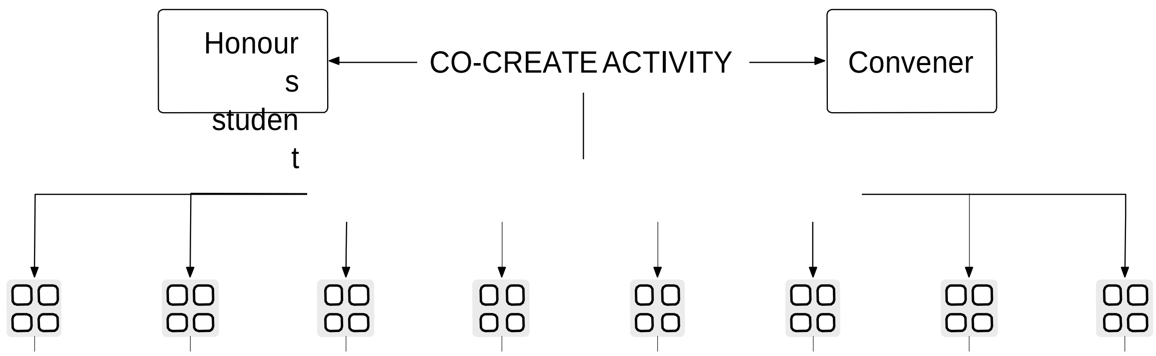
The course content covers introductory systems engineering principles, and the student- facilitated topics were divided into six topics:

- engineering life-cycle phases
- problem scoping and problem definition
- requirements analysis
- logical and functional flow analysis
- system architecture and subsystem integration
- testing and validation

Tutorials were typically made up of 24 students, divided into four project groups. In groups of six, students each chose a topic to co-facilitate on behalf of their group to the whole tutorial. This grouping creates a short-lived group of four—one from each project group—who were responsible for facilitating a topic each week. This approach adopts the jigsaw approach (Aronson 1978), where the nominated facilitator of the given topic becomes the expert on that topic and can share their knowledge with the rest of their project group (Rover and Fisher 1997, Tahir *et al* 2011). This model supports the finding that short-lived cross-group teams can be used successfully for additional learning (Felder and Brent, 2007).

The process for delivering the activity content is shown in Figure 1. For each topic week, a separate but often related activity was co-developed by a final-year engineering honours student with the course convener to illustrate key concepts from the theory. The honours students conducted human ethics-approved research using the activity as the basis for their research project. These activities were presented to the topic facilitators during a workshop session run by the course convener. The handout for this workshop is in Appendix A. Student facilitators were encouraged to adopt the activity or assimilate the activity with their own changes, and were not required to use it if they did not want to. In all instances, the facilitation groups adopted the activity with minimal alterations.

Observations were made during the activity and results were collected via a worksheet and summative quiz. Students were encouraged to participate in the activity as part of a normal learning environment, but were not required to participate in the research activity. A hierarchical diagram involving the key activities and participants is shown in Figure 1 for a cohort involving eight tutorial groups.



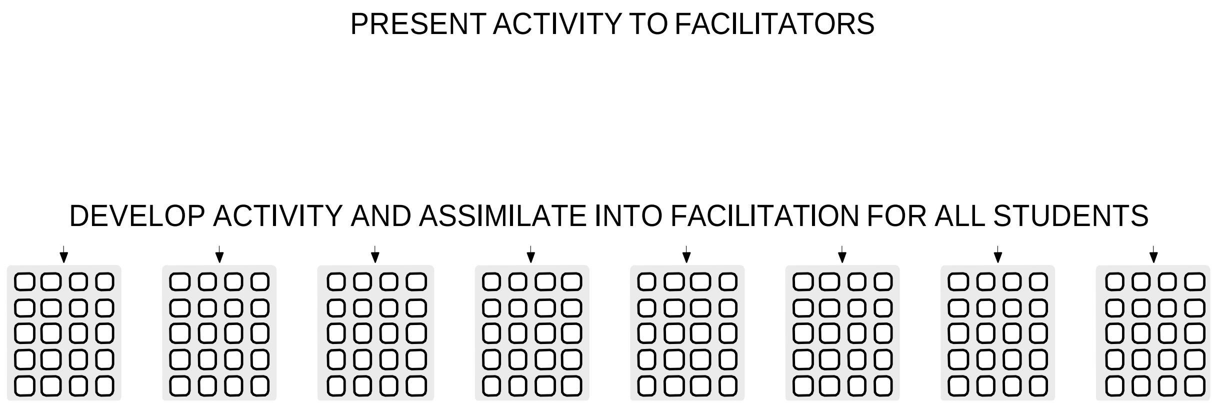


Figure 1: Hierarchy of actors and activities in the distributed learning activity

As opposed to the traditional lecture mode, this model meant that the teaching and learning was indeed distributed and de-centralised - from the activity's design through to the implementation and assimilation into each facilitation group's tutorial plan.

Activity design and methodology

The activity presented here was a hands-on exercise in the requirements engineering topic. The goal of the activity was for students to construct knowledge for themselves about trade-offs and evaluation processes. An orientation to the customer requirements had been given in classes previously and evaluation techniques had not been taught, although students may have self-studied ahead on this topic. Intuitive evaluation of ideas against alternatives is an important skill for an engineer to develop as she or he operates in the field, often with sub-optimal information in time-constrained situation.

Across the seven tutorials there were 23 facilitators, and 139 participant students provided their results for the study. Students worked in self-selected groups throughout this activity,ranging in size from 1 to 6. The groups were given three scenarios, each including a statement from a fictional character who required a bicycle to meet their needs. For example:

> *David is a first-year engineering student who requires a bicycle for off- roading with his mates from school. He will also use the bike to commute to classes on campus from his residential college. Since it is going to be used for both off-road and commuting, David requires a certain level of versatility in terms of comfort and performance. He expects the bike not to cost that much but is OK with maintaining his bike by himself.*

Students were then required to interpret the customer requirements as design requirements, and map them to the appropriate design attributes. This mapping is shown in Figure 2 complete with the requirements mapping.

Legend
1: Weak relationship
3: Moderate relationship
9: Strong relationship

		Design Attributes				
Design Requirements	Relative Importance	Cost	Maintainability	Reliability	Performance	Comfort
Comfortable	4					9
Maintenance	2	1	9	3		
Off-Road Ability	3				9	3
Low Final Cost	1	9			3	
Ease of Use	5					9
Direction of Improvement		↓	↑	↑	↑	·

Figure 2: Example worksheet with example pre-filled design requirements.paul

Note: the requirements mapping is represented in the grid that intersects Design Requirements and Design Attributes.

As the activity progressed through three scenarios, the amount of information presented in the mapping decreased, with students required to fill in the gaps:

- Scenario 1 included design requirements, relative importance, design attributes, direction of improvement and pre-filled mapping
- Scenario 2 required students to complete the direction of improvement and mapping for themselves.
- Scenario 3 required students to also interpret the design requirements and the relative importance

Once this requirements mapping activity was completed, students were asked to configure a bicycle from a set range of components to best meet the customer requirements. There were five alternatives for each component, and it was stated in the instructions that compatibility issues should be ignored[1]. The main components considered were: *Brakes*, *Wheels*, *Gears*, *Frame*, and *Saddle*. The components and alternatives are shown in Table 1.

Table 1: All possible alternatives for components in the bicycle configuration

Alternative	Brakes	Wheels	Gears	Frame	Saddle
1	Disc	Off-road	Shaft drive	BMX	Racing
2	Rim	BMX	Fixed gear	Road	Mountain bike
3	Drum	Road	Hub gear	Suspension	Comfort
4	Rollerbrake	Urban	Derailleur	Track	Banana
5	Coaster	Disc	Belt drive	Triathlon	Gel

The alternatives were displayed on separate, colour-coded cards. Each alternative was accompanied with a picture, description, and a star rating (out of 5) for the five design attributes: cost, performance, comfort, maintainability, and reliability. These were derived as an approximation based on research into the components, although were generalised to account for differences in product quality. Example cards are shown in Figure 3 for the gears, brakes and frame components.

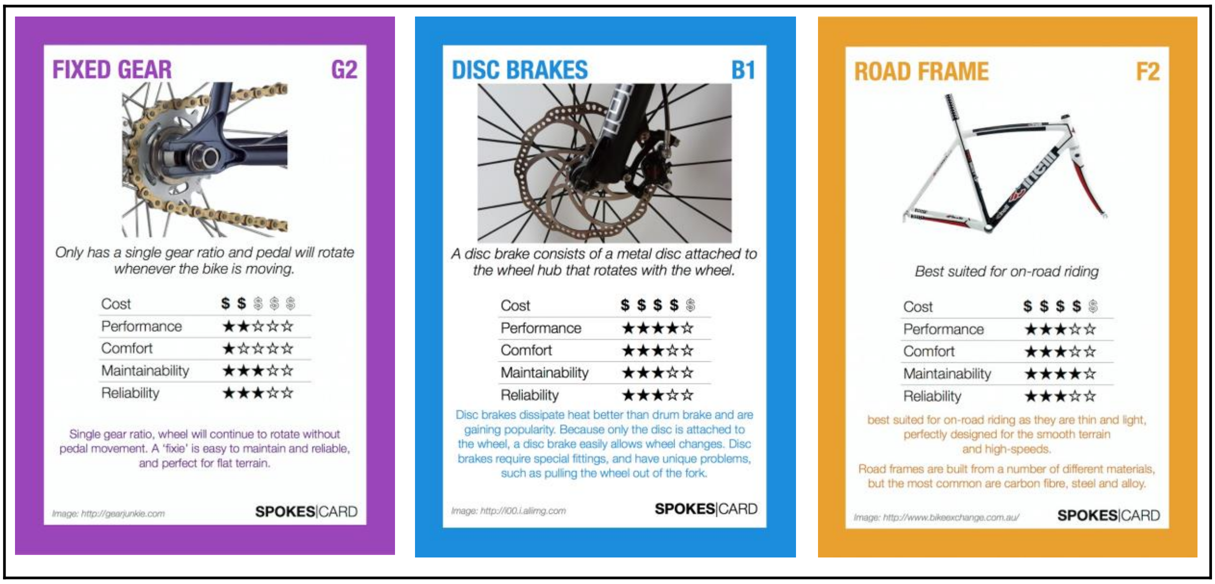


Figure 3: Example cards, showing the title, picture, descriptions and ratings against design requirements.

[1] note that the compatibility issues were raised in a subsequent discussion of system architecture. Ignoring compatibility issues meant that components could be configured in the activity in a way that is not possible or practical in reality; for example, installing road wheels on a BMX frame.

Groups were given approximately five minutes to configure the bicycle according to the customer requirements, and declare their selection on an A3 playing mat, shown in Figure 4.

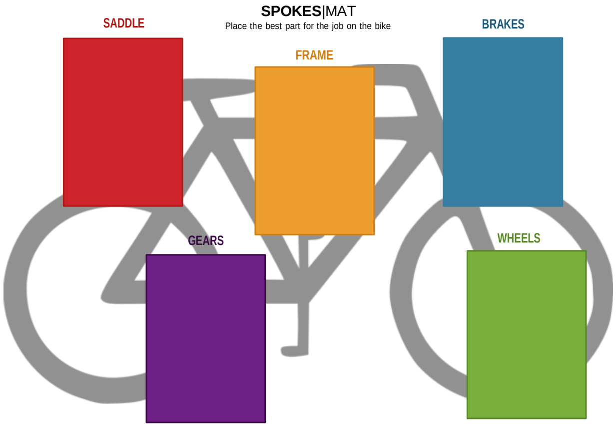


Figure 4: Playing mat for the declaration of bicycle configuration.

The configuration was then recorded by each group in an allocated space below the requirements map shown in Figure 2. At the conclusion of the tutorial, an individual quiz was administered that tested requirements mapping and asked for feedback in relation to the design of the activity.

Evaluation process

The results were collected on paper for each group during the activity, and an individual paper-based survey was conducted at the conclusion of the activity.

For the group results, the recorded configurations indicate aspects of the decision-making processes that groups went through to reach their conclusions. The configuration has been evaluated against a weighted evaluation matrix, shown in Table 2. Using this method, each selected component is compared, weighted and evaluated against the design requirements. The relative importance (R) is multiplied by the performance (P) given by each component against that design attribute on the card. The column totals are summed, resulting in a total score for that configuration. A complete listing of the components and performance is listed in Appendix B.

Table 2: Example weighted evaluation matrix, where the score is determined by the importance given in Figure 2, and ratings are supplied via the selected cards.

		W4 Urban Wheels		**G4** Derailleur Gear		**B5** Coaster Brake		**F3** Suspension Frame		**S2** Mountain Saddle	
Design Attribute	**R**	**P**	**R×P**	**P**	**R×P**	**P**	**R×P**	**P**	**R×P**	**P**	**R×P**
Cost	5	4	20	3	15	4	20	3	15	3	15
Performance	3	2	6	4	12	1	3	4	12	4	12
Comfort	2	4	8	4	8	5	10	4	8	3	6
Maint'abilty	4	4	16	4	16	5	20	4	16	4	16
Reliability	1	4	4	4	4	3	3	4	4	4	4
			54		**55**		**56**		**55**		**53**
								GRAND TOTAL			**273**

R: Ranking, P: Performance
Note: This represents the best possible configuration for these requirements

Given the information provided on the cards, specifically the star rating, students were expected to optimise their decisions based on maximising the star rating against the most highly ranked requirements. Ignoring compatibility issues, this would leave the client with the best configuration according to their requirements. However, in this time-constrained situation, non-optimal decisions may be made due to a particular interpretation of the requirements or personal preferences for bicycle components.

At the conclusion of the activity, an individual survey was conducted. It asked participants to interpret a separate scenario and generate a requirements map similar to that shown in Figure 2. These results were examined for completeness of components of six aspects: inclusion of design requirements, relative importance, attributes, mapping of requirements against attributes, units of measurement, and direction of improvement.

Results

With 5 alternatives for 5 components, a total of 3,125 configuration[2] options were possible given a fixed set of requirements. Results for all possible scenarios were simulated given the performance data shown in Appendix B to establish the ideal configuration based on the requirements. The results for group's configurations are reported as a percentage of the score for the ideal configuration (out of 273, as shown in Table 2).

Because the results were collected as a voluntary part of a learning activity, some groups elected not to submit their results, or failed to complete the activity during the timeframe provided by the facilitators. In this analysis, only the results for Scenario 1 are described. 38 groups participated in the activity and 37 groups provided results for Scenario 1. Groups ranged in size between 1 and 6 people. The group scores are plotted against the frequency of these scores in Figure 5.

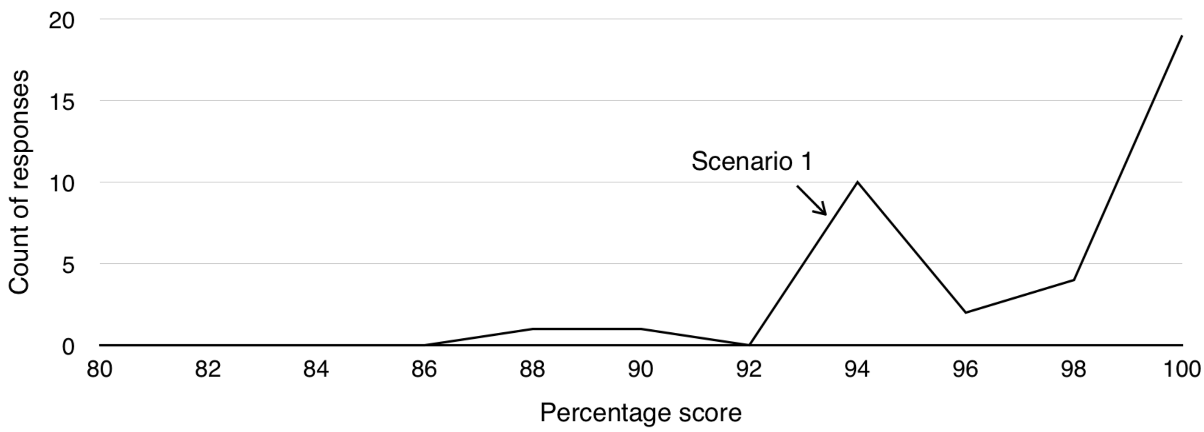


Figure 5: Plot of group response frequency with percentage score for Scenario 1 in the activity (bin size=2)

There are two obvious peaks in the count of responses. The optimal solution had 16 groups, with 3 groups achieving a close-to-optimal solution. A second peak of results appear between 92%-94% correct. The results in this bracket do not represent a single configuration, but rather seven different configurations that all compute to similar scores through the evaluation matrix. The breakdown of configurations are shown in Table 3.

[2] 5^5 configuration alternatives with compatibility concerns ignored.

Table 3: Configuration variations and count of configuration (blank cells in a row indicate results as per the optimal configuration)

Wheels	Gears	Brakes	Saddle	Frame	Count	# different from optimal	Score (%)

W4	G4	B5	S2	F3	16	NA	100.0
			S3		1	1	98.9
W2					2	1	98.9
W2			S3		2	2	97.8
W1					1	1	97.0
			S3	F1	1	2	97.0
			S4		1	1	95.6
		B4			1	1	94.8
W2		B4			2	2	93.7
		B4	S3		1	2	93.7
		B2			1	1	93.4
	G2		S3	F1	1	3	92.6
W1		B1			1	2	92.3
W3		B4	S3		2	3	92.3
		B2	S3		2	2	92.3
		B1	S5		1	2	88.2
W1		B2		F5	1	3	87.9
W4: 70%	G4: 97%	B5: 68%	S2: 68%	F3: 92%	37		

Note: percentage totals for W, G, B, S, F indicate percentage of optimal configurations for that component

The optimal configuration (W4, G4, B4, S2, F3) was achieved by 16 (43%) of groups. 7 groups had only one alternative components different to the ideal, with 10 groups having two alternative components different, and 4 groups with three alternatives different. The Gears and the Frame had only small variation of responses across the sample group, whereas the Wheels, Brakes and Saddle were more frequently changed. The most popular alternatives for Wheels were W2 and W1, B4 for Brakes and S3 for Saddle.

The optimal configuration consists of Urban Wheels (W4), Derailleur Gears (G4), Coaster Brakes (B5), Mountain Saddle (S2), Suspension Frame (S2). This optimal solution is not a solution that would work in the real world, largely due to the incompatibility of derailleur gears and coaster brakes, which can only used in fixed-gear configurations. For participants with specific knowledge about bicycle components, this may have guided their decision-making process.

Group size

Group size was not a controlled variable, as groups were self-selected. Groups of 2 members were the most common, most likely because that was the size suggested in the instructions. The frequency of group sizes and their results are shown in Figure 6. There were groups containing between 1 and 5 members that achieved the optimal solution. No group of 6 achieved an optimal solution. Groups of 4 members outperformed other group sizes, with all groups achieving the optimal solution.

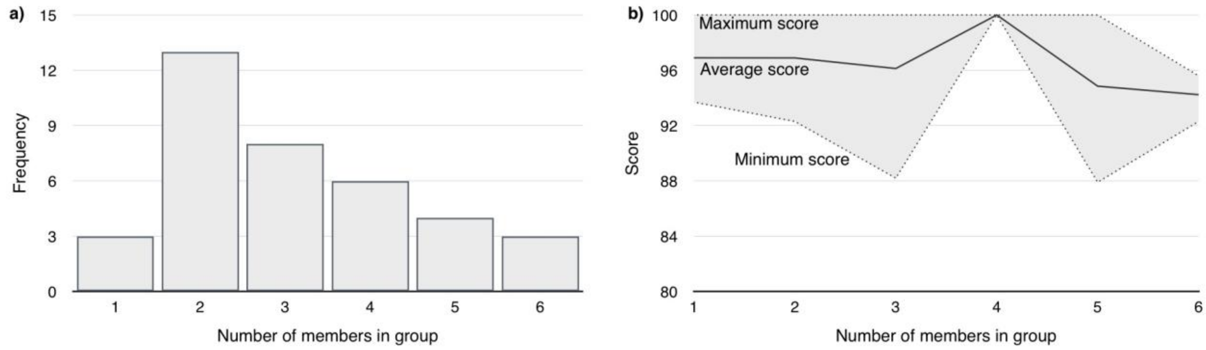


Figure 6: a) Histogram of group sizes; b) Range of scores according to group size.

Individual performance

The individual survey results were used to investigate how well individuals could transfer what they had learnt in the group activity to another situation: in this case, a household appliance. The test involved completing a requirements map, and individual surveys were marked only according to whether the individual had completed the aspect of the requirements mapping. The frequency of the responses containing aspects are shown in Figure 7a. The relationship between the score on the group activity and the score on the individual survey is shown in Figure 7b.

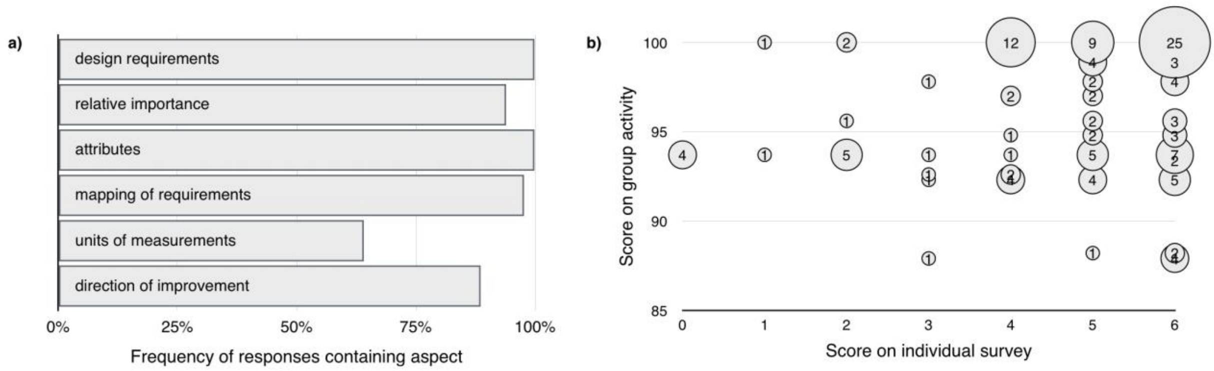


Figure 7: a) Bar chart of frequency of responses containing aspect in the individual survey;
b) Bubble chart of score on group activity compared with score on individual survey.

The results for individual performance show that students had the most difficulty indicating the units of measurement and the direction of improvement on the individual survey. Listing the design requirements and the relevant design attributes was almost universally completed. Figure 7b shows that within groups that achieved a similar score in the group activity, not all individuals demonstrated the same level of understanding about the underlying theory, shown through the variations on the individual survey.

Discussion

The key point for discussion is the process logic that groups went through to achieve the optimal solutions and make trade-offs. Because there were no compatibility constraints in the configuration, each alternative could be readily compared without consideration of other components. This should have led to a straight ranking of alternatives against the requirements in order of priority: *low final cost, maintenance, off-road ability,* *comfortable, ease-of-use*. We assume that these were considered according to the performance attributes given for each component—*cost, maintainability, performance, comfort, reliability*—but there is some ambiguity in these translations. For example, ease-of-use does not map well to reliability, but other options map adequately and this may lead to the group assuming that it is an approximate measure.

Table 4 is a summary of the popular alternatives chosen for each component. This highlights the trade-off decisions that were required in the activity. For example, although the most important requirements was cost, the best overall performing components across all the customer requirements were often not the cheapest. For example, the suspension frame was more expensive than the BMX frame but outperformed on other requirements.

Table 4: Performance of popular alternatives

ID	Description	(Low) Cost	Maint'abiility	Performance	Comfort	Reliability	Component Score
W1	Off-Road Wheels	2	4	3	3	5	46
W2	BMX Wheels	4	3	3	3	4	51
W4	**Urban Wheels**	**4**	**4**	**2**	**4**	**4**	**54**
G2	Fixed Gear	4	3	2	1	3	43
G4	**Derailleur Gear**	**3**	**4**	**4**	**4**	**4**	**55**
B2	Rim Brakes	4	1	2	3	2	38
B4	Rollerbrake	3	2	3	3	4	42
B5	**Coaster Brakes**	**4**	**5**	**1**	**5**	**3**	**56**
F1	BMX Frame	4	3	3	3	3	50
F3	**Suspension Frame**	**3**	**4**	**4**	**4**	**4**	**55**
S2	**Mountain Saddle**	**3**	**4**	**4**	**3**	**4**	**53**
S3	Comfort Saddle	3	3	3	5	4	50

Note: Best performing components are indicated in bold. All components are listed in Appendix B.

The total optimal score across the five criteria was achieved with:

W4, G4, B5, F3, S2 at 273 (100%)

in a weighted evaluation. The reason for groups not achieving an optimal solution may be due to alternative decision-making processes. A strategy for solving the problem would be if the group decided to consider the most important requirement (low cost) above all other requirements. In this case the selected components should be:

W2 or W4, G2, B2 or B5, F1, S2 or S3 (between 85% and 94%)

Only considering the top requirement, these options would lead to non-optimal solution. The biggest loss would be associated in the choice between Coaster Brakes (B5) and Rim Brakes (B2): although they are of similar cost, the Coaster Brakes performed much better than the Rim Brakes on other requirements.

If the group considered the top two requirements above all else, the selection would be:

W4, G2, B5, F1, S2 (94%)

However, if the group considered the performance against the top three requirements, then the selection would be:

W4, G4, B5, F3, S2 (100%)

where the options to choose G4 and F3 emerge to be better options[3]. Thus, evaluating alternatives to three levels of customer requirements is adequate in this scenario to achieve an optimal solution.

It is worth noting that the Gears and Frame were the components where there was least variation in the responses: G4 was chosen by 97% of groups and F3 was chosen by 92% of groups. However, the categories where there were biggest variation were when there was ambiguity at the top two requirements stage: Wheels, Brakes and Saddle, and selection of a non-optimal component here was not re-evaluated further in the decision-making. This suggests that when a group makes a selection where there is ambiguity, that they are more likely to stick to that option.

The group size is a noticeable observation from the activity; however, the activity was not designed to test for this due to the self-selecting flexibility of group formation. It does suggest, however, that groups of four or less are better at focused tasks like this. One trend that we expected to see going into the experiment was that groups of 5 might perform better, as the work may be divided up so that each team member was only concerned with one component, but we did not see this eventuate in the results.

In terms of evaluating the activity against the learning objectives for the session, the ultimate goal would be to a high frequency of students able to complete the requirements mapping task completely. There may be legitimate reasons for incomplete answers here, such as time limitation or confusion with the task. However, this is also an opportunity for further investigation in future activities.

The key observation from this learning activity in requirements analysis is that to achieve an optimal solution, groups were required to weigh up the top three of five customer requirements. Groups that evaluated only two alternatives were left making sub-optimal decisions.

Further work

Beyond examining the effect of group size and the connection between the group activity and individual learning, there are three key areas of further work that immediately arise out of constructing this learning activity.

First is to examine the variable relationships in the given context: for example, whether different performance values would influence the outcome. This could be examined if the optimal solution could only be derived when considering all requirements, or if the requirements themselves didn't map directly to given component attributes.

Second is to examine the effect of constraints on the decision-making process. An example of this in this activity is the component conflict between Coaster Brakes and Derailleur Gears, which are incompatible components in the real world. If there was a mechanism that allowed for the identification of constraints, the decision-making process would be more challenging and may demonstrate different results.

Third is to examine the role of feedback in the decision-making process. In this activity, students were only required to declare their configuration, and then discuss their justification with the class. In future versions of this activity, the ability for a group to achieve a score by comparing their solution to the ideal solution could help groups to make better decisions over iterations of decisions. For example, if the activity was in the form of an electronic game, where feedback was instantaneous, students may be able to achieve a more optimal configuration very quickly, and compatibility issues could be included as an extra level of difficulty to challenge students.

[3] for the first three requirements: F1: $4 \times 5 + 3 \times 4 + 3 \times 3 = 41$ and for F3: $3 \times 5 + 4 \times 4 + 3 \times 4 = 43$

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Acknowledgements

The authors would like to acknowledge that this work was made possible through a Teaching Enhancement Grant at The Australian National University that enabled funding for the creation of activity. We would also like to acknowledge all of the student facilitators that ran the activity (often with unenviable passion) as part of their tutorial facilitation.

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Appendix A

Suggested plan given to students for the running of the activity.

SPOKES|Game ACTIVITY GUIDE
Systems Engineering

Activity Summary:
Divide students into groups of 2-3, and challenge them to build the perfect bike in the given scenario using a House of Quality (HoQ).

Learning Outcomes:
1. Develop understanding of the relationships between customer requirements, design requirements and design attributes
2. Use this information to make effective initial design decisions

Time Allocation: Total:
30 minutes
About 5-10 minutes for each scenario, plus time to discuss results.

Required Materials:
- Spokes card set for each group
- Spokes mat for each group
- Three scenario sheets
- Group number card
- Prepared slides to help explain the activity

Activity Breakdown:
Divide class into groups of 2-3, and distribute a mat and set of cards to each Use the slides to explain the activity and how it will be carried out (1 min)

For each scenario, allow 5 minutes:
- Hand out the blue activity sheet
- Show slide for scenario and commence activity
- Wait for groups to fill out scenario sheet while answering any questions groups might have (5 min)
- Once scenario sheet has been filled, move to the next scenario (5 min)

Suggested prompts:
For Scenario #1:
- Construct your perfect bike by studying the HoQ's given requirements and ratings.

For Scenario #2
- Study your scenario and requirements, fill out the ratings and design your bike

For Scenario #3
- Study your scenario and understand your customer's requirements
- convert these into design requirements,
- fill out your HoQ and design your bike.

Linking activities
- Describe the HoQ with TPMs
- Discuss the difference between design requirements and engineering characteristics
- After the activity, discuss the types of trade-offs that the groups found

Appendix B

Evaluation of alternative configurations. Scores are calculated using a weighted evaluation: Cost x 5 + Maintainability x 4 + Performance x 3 + Comfort x 2 + Reliability x 1

ID	Description	(Low) Cost	Maint'abiility	Performance	Comfort	Reliability	Component Score
B1	Disc Brakes	2	3	4	3	3	43
B2	Rim Brakes	4	1	2	3	2	38
B3	Drum Brakes	2	2	3	3	3	36
B4	Rollerbrake	3	2	3	3	4	42
B5	Coaster Brakes	4	5	1	5	3	56
F1	BMX Frame	4	3	3	3	3	50
F2	Road Frame	2	4	3	3	3	44
F3	Suspension Frame	3	4	4	4	4	55
F4	Track Frame	1	4	4	3	5	44
F5	Triathlon Frame	2	4	4	3	4	48
G1	Shaft Drive	2	3	3	4	5	44
G2	Fixed Gear	4	3	2	1	3	43
G3	Hub Gear	2	1	4	4	4	38
G4	Derailleur Gear	3	4	4	4	4	55
G5	Belt Drive System	1	5	4	4	5	50
S1	Racing Saddle	2	4	5	3	3	50
S2	Mountain Saddle	3	4	4	3	4	53
S3	Comfort Saddle	3	3	3	5	4	50
S4	Banana Saddle	3	3	1	4	3	41
S5	Gel Saddle	1	3	2	4	3	34
W1	Off-Road Wheels	2	4	3	3	5	46
W2	BMX Wheels	4	3	3	3	4	51
W3	Road Wheels	3	3	4	4	3	50
W4	Urban Wheels	4	4	2	4	4	54
W5	Disc Wheels	1	4	5	3	4	46