On the Impact of Systemic Thinking in Sustainable Design

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Abstract

The world faces significant problems of high complexity. The potential of knowledge, methods and tools used in design education and practice are useful for the development of sustainable solutions. Sustainable design is regarded in this paper as the integration of multiple competencies in order to generate and implement creative interventions that trigger positive changes in complex socio-technical systems. In this paper, a multidisciplinary case study is created for experimentation on the way in which different student groups approach complex problems, the type and level of thinking used, and the evaluation of the adequateness of their proposals by experts. The groups analysed encompass eighty subjects enrolled in four different undergraduate and graduate programs. In the experimental groups, the lecturers integrated a number of methods and tools that target purposeful change in complex adaptative systems. In the control courses, the lecturers applied the more traditional methods and tools that are customary of their disciplines, without explicit linkage to complexity and systemic change. Students participated voluntarily in a team activity dealing with the pervasive and complex problem of garbage disposal and transportation in large urban settlements. The resulting proposals provide valuable insights, for example regarding the way in which students analyse the situation, the type and level of change that their proposals imply, and the scope and depth of their causal analysis. This study demonstrates that the set of methods and tools currently used in some of our courses are valuable tools for promoting systemic thinking in our students. Evidence is also provided to suggest that regarding systemic reasoning, the distinctions between disciplinary and multi-disciplinary teamwork may be weaker than what was expected. Furthermore, diagnosing systemic thinking in a team or a person would remain largely irrelevant if this type of reasoning failed to produce more creative and higher quality responses. Our study confirms the premise that teams with high-order systemic thinking consistently yield high-quality and original solutions.

Keywords

systemic thinking; design education; sustainable design; complex systems; creativity.

Rethinking systemic sustainability

The world faces a number of significant social, economic and environmental problems of high complexity, for example as a result of population growth and resource depletion. The potential of knowledge, methods and tools used in design education and practice are increasingly being recognised beyond the areas conventionally associated with the design disciplines, i.e., products, buildings, visual communication, and digital media. Strategies, services and experiences designed to address complex problems are being considered of key relevance for creatively conceiving and implementing sustainable solutions across the disciplines. The work presented in this paper emerges from the coincidence of a group of scholars from diverse disciplinary backgrounds who share a deep concern about the type of creative thinking that may be necessary to develop in our students if they are to face the complex problems in years ahead.

Sustainable design is here considered beyond currently limited interpretations such as the use of recyclable and certified materials, 'green' gadgets, or bioclimatic buildings. Sustainable design is regarded in this paper as the integration of multiple competencies in order to generate and implement creative interventions that trigger positive changes in complex socio-technical systems. Such a broad view of design is likely to demand a disruptive change in how we educate designers today. Moreover, it may demand a major review of education in general, for instance by integrating strategic design skills in all disciplines including engineering and business.

An implication of this paradigmatic change of view of design, is that the established design disciplines do not have the prerogative in the purposeful formulation of creative interventions in complex systems. Arguably, n-disciplinary teams (where multiple or n disciplines are integrated) are more likely to achieve creative collaborative interventions than teams from any separate discipline alone. Such teams may find design strategies, methods and techniques to be valuable in the generation of creative solutions to complex problems. Nonetheless, to our knowledge, there is insufficient evidence available to date regarding the contribution of design principles beyond ambiguous buzzwords like “design thinking”.

In this paper, a multidisciplinary case study is created for experimentation on the way in which different student groups approach complex problems, the type and level of thinking used, and the evaluation of the adequateness of their proposals by experts. The groups analysed include four undergraduate courses and two multidisciplinary graduate courses encompassing a population of eighty subjects enrolled in Industrial Design, Electronic Engineering, Manufacturing Systems and Business Administration.

In two experimental groups, the lecturers integrated a number of methods and tools throughout the semester that target purposeful change in complex adaptative systems. In the four control courses, the lecturers applied the more traditional methods and tools that are customary of their disciplines, without explicit linkage to complexity and systemic change. Students participated voluntarily at the end of the semester in a three-hour team activity dealing with the pervasive and complex problem of garbage disposal and transportation in large urban settlements. The resulting proposals provide valuable insights related to the impact of educational interventions, the composition of multidisciplinary teams, and the way in which students analyse complex situations.

The following section of this paper briefly introduces the theoretical underpinnings of systems thinking and introduces the concept of systemic thinking. Section 3 presents the context of our case study and our research hypotheses. Section 4 details the experimental details of our work. In section 5 the main results are analysed. Finally, section 6 presents a discussion of the significance of this work and concludes with a future research agenda to develop toolkits for systemic thinking.

Targeting sustainability through systemic thinking

Systems thinking has been defined as the type of problem-solving reasoning skills that deal with how causes and effects interact adopting a non-reductionism approach [3]. Existing frameworks distinguish basic/low-level, intermediate/mid-level and advanced/high-level systems thinking styles [6]. In other words, this range has also been defined as systematic or analytical thinking in the lower end, to systemic thinking in the higher end [7]. The term “systemic thinking” also corresponds to higher-order cognitive skills (HOCS) [11].

Systemic thinking describes the cognitive processes that “see relationships rather than things; cause-effect relations as reciprocal; multiple causes/multiple effects; and system structures that cause system behaviour” [2]. This level of reasoning is distinguished from basic or low-level reasoning, which is ascribed to subjects who “see things, not relationships; see cause-effect relations as one-way: one cause/one effect; and external events causing system reaction” [2]. Systemic thinking is valuable for sustainability because it “enables the dealing with complex systems with the appropriate scope, depth, versatility and insight to generate qualitative changes that increase the sustainability of products and systems” [1].

In order to characterise and diagnose systemic thinking, in this paper we adapt a three-tier framework based on [2, 9] where ideas generated by subjects are classified from low-level (SL), to mid-level (SM) and high-level (SH) systems thinking. At the base of this range, SL corresponds to systematic and analytical reasoning that is based on recognising variables, ascribing simple causal explanations, is aimed at system-wide solutions, and is focused on improvements and efficiency. SM integrates the linkages and relations between variables, identifies scales and stages in the system, generates strategies based on expected future effects including indirect consequences, and recognises stakeholders and information flows. At the top of the range, systemic thinking (SH) emerges when the person adopts a wider view of the system and shows evidence of reasoning about contextual and situational conditions, feedback cycles, second-order interactions, system trajectories, and exogenous trends and influences. SH includes reflection on the role of the problem solver in understanding, framing and approaching the problem. The SH person learns within the situation at hand and aims to develop new strategies, models, and policies that trigger sustainable paradigm changes.

We define “sustainable strategy proposal” here as a simple yet comprehensive approach to a complex problem that considers its economic, social and environmental dimensions. Such proposals are difficult to evaluate upon their generation, since their impact in transforming the system is fully understood only after their contingent implementation; but their potential can be estimated, particularly by experts [3]. Recent examples of sustainable strategy proposals include massive urban transportation systems, integrated energy and waste management systems, and other initiatives that address a large number of issues and stakeholders, anticipate first and second-order consequences, promote positive feedback cycles, deal with information flows and power structures, reveal hidden connections between system elements, seek emergent results, etc. Creative value is associated with SH, as there is wide consensus about its potential to transform paradigms and open new solution spaces [27].

Assessing systemic thinking across disciplines

This paper extends previous work where systems thinking was analysed in design and engineering students [1]. The goal here has been to extend our sample population, improve our experimental design, and to incorporate business students in our studies. In particular, the aim of the work presented here is to provide insights regarding the effectiveness of current teaching strategies and methodologies in achieving systemic thinking and creative responses in our students. The long-term objective of our work is to understand the role of creativity and innovation methods and group dynamics in promoting systemic thinking to empower n-disciplinary teams to achieve sustainable strategy proposals. Starting points for this inquiry include: to test the validity of these learning activities in the development of systemic thinking, to assess the relation between systemic thinking and multidisciplinary teamwork, and to understand the role of systemic thinking in the synthesis of valuable and creative solutions.

Hypotheses development

Being consistent with the theory developed in the literature discussed in section 2, we would expect that our teaching interventions designed to cope with complex problems will have an impact on the level of students’ systemic thinking when approaching with complex situations. Considering this, we propose the following hypothesis:

H1: "A combination of methods and activities geared towards the creative intervention of complex problems has a positive effect on the development of systemic thinking"

Considering that the level of heterogeneity in ideas among a group of people from different disciplines and backgrounds will be higher with respect to same-discipline groups, we expect that multidisciplinary teams will tend to provide a more systemic view of a problem due to the variety of ideas and information emerged from the team. Therefore, we propose the following hypothesis:

H2: "Students who work in n-disciplinary teams show increased systemic thinking compared against those in specialized or uni-disciplinary teams"

Finally, we expect that those teams with a higher systemic view when facing complex problems will be more likely to suggest more effective and creative solutions compared with teams with lower systemic view. Therefore, we propose the following hypothesis:

H3: "The level of systemic thinking of teams will be positively related to the quality of their strategy proposals"

Research methodology

We did an experiment using 28 different teams of students across three academic disciplines: design, engineering and business. For the first two hypotheses we created treatment and control groups – intervened vs non-intervened teams, and disciplinary vs non-disciplinary teams. We wrote a real-world case study in which we describe a complex situation. Each team had to work on the problem and propose a possible solution. In the following sections we describe in detail how we set up the experiment.

Educational settings

This section provides a brief description of each course and summarises the experimental conditions of our study. Six courses were selected from the Bachelor and Master programs at Tecnologico de Monterrey (Queretaro). The authors are lecturers of these courses, thus providing access to experimental activities throughout the semester. In two of these courses, the authors have been gradually incorporating teaching strategies, methods and tools related to sustainability and in particular, to the design of creative interventions in complex adaptive systems.

The first four groups selected for our study include three undergraduate courses from the Electronic Engineering, Industrial Design and Business Administration programs, and a graduate course from the MBA program. These cases are labelled as “non-intervened” because their emphasis is not on the generation of change initiatives in complex systems. Two of these cases are courses that do deal with innovation, entrepreneurship and sustainability principles, but do not incorporate the specific toolkits and their application in applied projects. The two remaining groups are an undegraduate course from the Industrial Design and a graduate seminar from the Master of Science in Manufacturing Systems. These courses are taught by different lecturers, and they are both based on team projects where the students apply methods and tools expressly aimed at triggering change processes in complex adaptive systems that include social, economic and environmental problems. The following coding is used to distinguish the groups:

a. Disciplinary (D) or Multidisciplinary (M)

b. Intervened (I) or Non-intervened (N)

c. Undergraduate (U) or Graduate (G)

Non-intervened (N) groups

- Course title: "Design of social-based wireless personal and body area networks" (DNU01) Last year of the Bachelor of Computer Systems and Computer Science. This is a project-based elective course on Wireless Personal and Body Area Networks (W-PAN/BAN). The course includes laboratory practices and the development of a project including the following stages: problem/need identification, idea generation, solution election, prototyping, and final presentation. The project incorporates a social-based framework for the design of technological systems to address social problems. The course also incorporates visits to industry, creativity sessions and principles of intellectual property. The final projects were submitted to the "Bluetooth Innovation World Cup 2009" [12].
- Course title: "Innovation by design" (DNU02). Final year seminar of the Bachelor of Industrial Design. The goal of this seminar is to introduce students to the reflexive practice of innovative design. At this stage, students have undertaken six design studio subjects in a wide range of themes and in an increasing degree of complexity. The design projects in those learning experiences had focused mainly on form, function, user and manufacturing issues, but they left unaddressed the complexities of innovative business strategies. This seminar challenges students' notions regarding the role of creativity, design and innovation, and provides concepts and techniques to incorporate strategic innovation into their design practice. The seminar includes a partial term on sustainable development, but the nature of this seminar is mainly theoretical and reflective, and does not include project development.
- Course title: "Information Technology Management" (DNU03). Second-year undergraduate course for Business majors. This course focuses on the operational and strategic role of information technology in the organization as well as on individual information-seeking skills. The main objective of the course is to learn how information technology can enhance organizational efficiency and even transform business strategy. The students practice their

abilities to search for, analyze and organize information using up-to-date information technology tools.

- Course title: "Innovation and Entrepreneurship" (MNG). First-year graduate course for the Master of Business Administration. This course focuses on the the challenges of entrepreneurial innovation and product/process design within a business model. More specifically, students acquire hands-on experience on identifying a social need, looking for business opportunities accordingly, and then the students have to come up with a sustainable business model to address those social needs and exploit the business opportunity. In addition, students are exposed to real-world entrepreneurship experienceses with local entrepreneurs, and also they receive lectures about innovation and business models. At the end of the course, students grouped in multidisciplinary teams present a business model as a final evaluation. They have to provide evidence for the social need, and also they have to show evidence of market, technical and financial feasibility.

Intervened (I) groups

- Course title: "Systems thinking design studio" (DIU). Eighth semester of the Bachelor of Industrial Design. This design studio addresses design interventions in complex social, economic and environmental systems. As is customary, students tend to think first in the design of consumer products. Through group debates around sustainability, ecological footprint, life-cycle assessment, consumerism, social wellbeing and biomimicry, students reinterpret their project goals in order to surpass the realm of objects. Concepts related to systems and services emerge, and the team proposals increasingly encompass a complex network of innovative decisions about people, economics, politics, markets, function, semiotics, production processes, nature, etc. The orientation of this design studio has yielded results with extraordinary potential for positive impact in our society, including the project "Waste Recovery System", a 2009 finalist in the prestigious Index Design Award [13].
- Course title: "Creativity and innovation graduate seminar" (MIG). Second-year seminar of the Master of Science (Manufacturing Systems). Students from multiple backgrounds converge in this course including Mechanical Engineering, Industrial Engineering, Industrial Design and the Master of Business Administration. This seminar seeks to promote reflection on the innovative potential of research projects and entrepreneurship initiatives. Teams of students develop a value proposal to an external client, addressing the clients' current problems and strategic planning. Students seek to introduce disruptive changes in their clients' practices rather than mere incremental improvements. The theoretical principles as well as their practical application deal with Systemic Complexity. Cases are analyzed and discussed in class, students write essays related to these themes, and the final project is evaluated by the client. As a result of this seminar in Fall 2009 one project was selected by the Business Incubator program and its business plan is currently under development.

The methods and tools used in design groups (DIU, MIG) are selected from the literature and from the authors' professional and teaching experience with the aim to enable and support systemic thinking. They include:

- Activity name: "The roots of the problem". Film screening of documentaries and movies dealing with social and economical complex problems as well as sustainable development. This material is selected thinking on the clear exposure of global problem roots. The objective is to move students from their comfort zone and trigger controversy for the debates following the screening. “Home” [14], “1984” [15], “Story of Stuff” [16], “An Inconvenient Truth” [17], "Hans Rosling TED talk" [18].
- Activity name: "Prosperity without growth". Class debates around the topics of how the current problems of social disintegration, lost of cultural heritage, economic gaps among social groups and nature depletion have reached their actual state. The relations between these problems are discussed, and the class identifies paradigms to be changed in order to achieve sustainability and social justice within global prosperity. Debates are open and the

objective is to help students reflect on these issues and their own personal and professional goals.

- Activity name: "Visualizing the system". System structure graphic visualization, this could be done physically or virtually in two-dimensional compositions, the objective is to visually understand the relation among the stakeholders and the exchanges they have, [19].
- Activity name: "User-centred Design". Surveys, interviews, behavioural mapping, camera journals and story telling; the main objective of using these tools is to understand as deep as possible the state of the system, develop stakeholder empathy, and elucidate their true needs, desires and expectations. Depending on the nature of the stakeholders (these could be any actor in the system with any type of exchange with others), students must select the apropiate tool and apply it to provide evidence of their understanding [10].
- Activity name: "Designing the change". Sketch, mind-mapping, and dirty prototypes are commonplace in all design studios, all these tools are implemented searching innovative ideas to be applied into the systems or to solve a particular aspect, like a specific product. The deliverables vary according to the project, from physical models, two-dimensional maps, photo-journals or drawings.
- Activity name: "Dancing with systems". This activity analyses the possible points of intervention in a system following a hierarchy of leverage points [3]. The objective is to create proposals of intervention in the semester project taking into consideration the consequences and the impacts throughout the system. Intervention proposals are analysed by an expert in each relevant area according to the project under development. Biologists, chemists, manufacturing engineers, biotechnologists, physicists, economists and lawyers are customarily consulted. The deliverable of this activity is a map of the system with the interventions and its new exchanges and expected consequences as advised by the experts.
- Activity name: "Complex problems may have simple, optional and unexpected solutions". This activity aims to introduce students to the idea that complex problems in large systems may be addressed by enabling counter-intuitive minimal changes that trigger positive effects. The three key issues in this approach are: to present the solution as an optional alternative in the system and not as a compulsory course of action, to focus on experimental evidence to select the smallest change (in cost, effort or time) with the largest returns, and to bet on counter-intuitive system dynamics. This activity is approached through the principle of "Nudge" by Cass Sunstein and Richard Thaler [20] where evidence from the literature and a range of methods are well documented. The deliverable of this activity is a one-week project where students design and document a 'nudge' that causes a behavioural change in their context. Pirnciples and examples of abductive reasoning are also useful for this activity.
- Activity name: "Identifying the growth and destruction of value in complex systems". The aim of this activity is to help students identify the values that the stakeholders of a complex system may perceive from its current state. Students realise that cycles of corruption and other negative behaviours often times respond to perceived values that reinforce negative outcomes. In design projects, this value-construction dimension of complex systems is best approached by learning the process of creative destruction in innovation [21], the dynamics of the Function-Behaviour-Structure framework [22], and the value of breakthrough products [23]. The deliverable of this activity is a team presentation where students seek and document examples of systems that yield undesired outcomes, and provide a value-based explanation of such outcomes.
- Activity name: "Life-Cycle Intelligence". This activity introduces students to decision-making processes based on a deep understanding of the life-cycle of a product or a service system, starting from the inputs, materials and supplies, throughout use and disposal. Simplified versions of LCA methods are used, such as the "Life Cycle Design tools" of the LeNS project [28]. Notions associated to "Ecological Intelligence" [24] provide an adequate starting point. The deliverable of this activity is to reveal, estimate and document the hidden costs of the team's main design project in the semester.

- Activity name: "Personal Sustainability Project". This activity provides students with first-person experience of changing deep-rooted habits in order to decrease their environmental footprint. Students use a number of online calculators to estimate their footprint and to identify the undesired consequences of their routine activities and everyday choices of transportation, food consumption, etc. The deliverable of this activity is a four-week journal where students record the challenges and milestones of their attempt to reduce their footprint. An essay is submitted by the end of this activity where students discuss the strategies that they would propose to help others implement this type of change.

	D/M disciplinary multi	I/N intervene non-interv	U/G undergrad graduate	Class size	Responses	Number of teams	Design (D)/ Engineering (E)/ Business (B)
DNU01	D	N	U	15	15	5	E
DNU02	D	N	U	25	5	3	D
DNU03	D	N	U	12	7	3	B
MNG	M	N	G	17	16	5	E/B
DIU	D	I	U	25	25	9	D
MIG	M	I	G	13	13	3	D/E/B

Table 1 Summary of all 28 teams included in this case study. 16 control teams (N) and 12 experimental teams (I); 20 are disciplinary (D) and 8 multi-disciplinary (M).

The case study

In our experiment we wrote a case study that deals with the problem of waste disposal and recycling in urban and suburban residential areas. Then we asked our student teams to provide a solution for this case. We created this case study based on exhaustive information from a consultation project developed for the Miguel Hidalgo local government in Mexico City in 2007. The case was jointly developed by the authors considering its suitability and relevance across all disciplines. The case of waste disposal and recycling was chosen because it provides high complexity and presents a significant challenge for the development of local solutions that add value to the economy, society and environment [25]. The time allocated for this work is three hours during the last session of the semester, and participation is voluntary and independent from the course grades.

Student teams in control groups are formed, given a design brief about residential waste disposal and allocated a two-hour session to analyse and discuss the problem and to formulate a sustainable strategy proposal. At the end of this session, teams are required to formulate a plan to address the problem specifying the resources required, expected results, etc. Two types of control groups are studied here: uni-disciplinary and n-disciplinary groups, the first refers to specialized teams of only business, design or engineering members while the second refer to teams that integrate these disciplines.

Experimental groups are also presented the same design brief and allocated a two-hour session under equivalent conditions, except that a summary of the topics and projects covered throughout the semester is presented highlighting the methods and techniques aimed at triggering change in complex systems. In a one-hour preliminary activity, students of these groups are reminded of the several methods covered throughout the semester. A set of qualitative research methods is used to assess both the process and the product of this short activity: questionnaires are applied to the team members immediately after their participation, sessions are recorded in video for further analysis and interpretation, and a panel of (independent experts) evaluates the potential of the proposals from a sustainability and innovation viewpoint.

The assessment tool

The assessment tool is divided in two parts; firstly, a one-page scenario provides information about the current situation including the agents involved in the collection, transportation and sorting of garbage. Statistics and the general flow and interactions between agents are included. The main challenges and conflicts of the system are summarised. Students analyse and discuss the current situation in order to collaboratively develop a solution strategy proposal. Teams are required to submit the following information at the end of the two-hour session: a one paragraph summary of the team's analysis of the current situation, a one-paragraph summary of the strategy that the team proposes in order to approach the problem, and a three-paragraph explanation and justification of the team's consensual ideas highlighting the main objectives, expected outcomes, and the creative value of their ideas.

These teams' responses are reviewed by the researchers in a double-blind process, yielding a classification of the solution strategies in SL, SM or SH according to the three-tier framework presented above in section 2. As a result, the solution strategies developed by teams are independently categorised by 'systemicity' and quality criteria including its creative potential to trigger paradigm changes. The distance between the distributions of SL, SM and SH in N and I groups is the vehicle to validate H1. The distance between the distributions of SL, SM and SH in D and M groups is the criterion to evaluate H2. Lastly, the distribution of quality and SH across all groups is the means to evaluate H3.

The second part of the case consists of a questionnaire that students respond individually after submitting the team's strategy proposal. This questionnaire is based on the strategies proposed by Meadows to intervene systems [3] and is used to compare the level of systemic thinking in individuals and teams.

Results

We categorized team's responses according to the level of systemic thiking and computed a standardized systemic thinking score. We tested H1 and H2 using a two-group-mean comparison t-test. For H2 we run a simple linear regression, and also run a two-sample-mean comparison t-test. Our data provides support for H1 and H3, but not for H2. Tables 2, 3 and 4 show the statistical results for these hypotheses.

Variable	Mean of Intervened teams (N=12)	Std error Intervened teams (N=12)	Mean Non-Intervened teams (N=16)	Std error of Non-Intervened teams (N=16)	t-statistic of the mean difference	Statistical significance of diff. between groups (p-value, 1-tailed)
Systemic thinking score	1.99	0.11	1.60	0.10	2.56**	0.0083**
Solution quality	2.34	0.17	1.74	0.13	2.80**	0.0048**

Table 2 Difference between systemic level score and solution quality between intervened vs non-intervened teams. Note: ** significant level at 0.01 level

Figure1 illustrates the information about systemic thinking levels:

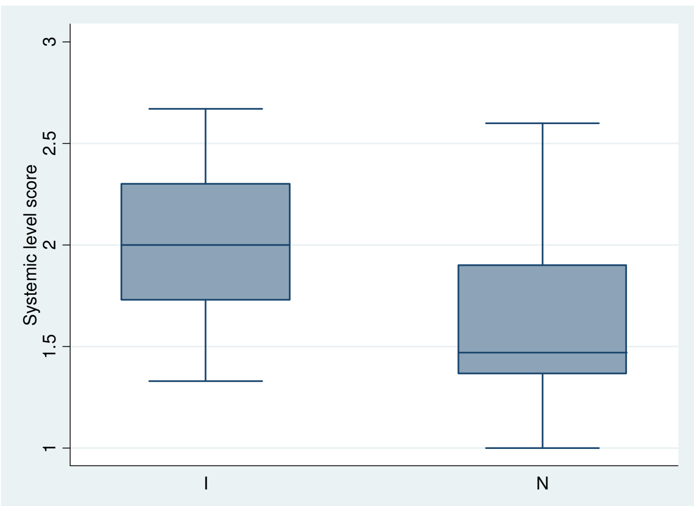


Figure 1 Box plot of the systemic level between Intervened (I) vs non-intervened (N) teams

As we can see from Table 2, there is significant difference between the level of systemic thinking between the intervened and the non-intervened teams. The intervened teams exhibit significantly higher level of systemic thinking compared with non-intervened teams (p-value=0.0083). If we can provide support to H3, then it would make sense to argue that intervened teams compared with non-intervened teams will experience a higher quality in their solution to the case. As we can see, we provide statistical evidence for this argument (p-value=0.0048). Therefore we provide strong statistical evidence for H1.

Variable	Mean of Multidisciplinary teams (N=8)	Std error of Multidisciplinary teams (N=8)	Mean of uni-disciplinary teams (N=20)	Std error of Non-Intervened teams (N=20)	t-statistic of the mean difference	Statistical significance of diff between groups (p-value, 1-tailed)
Systemic level score	1.71	0.13	1.79	0.13	0.42	0.33
Solution quality	2.00	0.21	2.00	0.14	0.00	0.50

Table 3 Difference between systemic level score and solution quality between intervened vs non-intervened teams.

There is not enough significant evidence to support H2. Multidisciplinary teams and uni-disciplinary teams do not show significant difference in their levels of systemic thiking. The difference between both groups' quality of solution is not statistically significant either. Therefore, H2 is not supported.

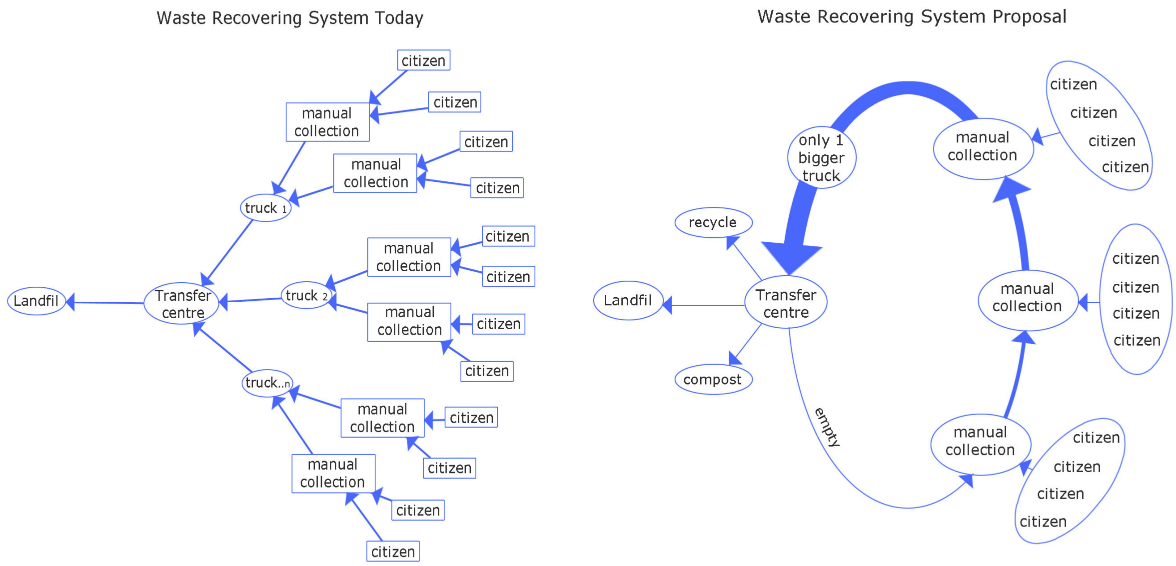
For H3, we run a simple linear regression using solution quality as dependent variable and the level of systemic thinking as independent variable. Regression results show that these two variables are positively correlated (correlation=0.31, and this correlation is marginally significant at the 0.055 level). We run an one-way ANOVA to see whether these three groups experience different levels of solution quality, finding significant difference between the groups (F=10.42, p-value=0.0005). After running Bonferroni comparisons, we found that SH teams receive a significant higher level of solution quality compared with SL teams (p-value=0.003). We also found significant difference in the level of solution quality between SL teams and SM teams (p-value=0.001). However, no significant difference between SM teams and SH teams was found. Considering these results we can say that H3 is supported.

To evaluate all three hypothesis at the same time, we run a multiple regression model with systemic thinking level as dependent variable and the dichotomous variables team type (Multi/ uni-disciplinary) and intervention variable (intervened/non-intervened) as independent variables (results are not shown in this paper due to space constraints). We also added as a control variable the academic level of the team (undergraduate/graduate). Interestingly, over and above all variables, the fact that the team is intervened was the only one significant in the model. We did a further analysis, regressing all these dichotomous variables and also the level of systemic thinking on the solution quality as dependent variable. For our surprise, the variable intervention explained most of the variance of the solution quality.

Besides these quantitative results, in the following section we present exemplary cases to illustrate the qualitative evaluations of the team's proposals.

Exemplary systemic strategy proposals

Two strategy proposals developed by our students are documented in this paper as exemplary SL and SH responses. Team PLP of group DIU presented a majority of SM and SH responses, and received the highest quality score of all 28 teams. This team's main idea is to reorganise the network of garbage collection and waste recovery with the objective of minimising the number of trucks and optimising the manual collection process in the system. Rather than having half-empty trucks doing short trips from every existing small collection point to the transfer centre, PLP's strategy is to estimate the type of truck and route design that could traverse a number of larger collection points to deliver their contents in one longer trip into the transfer centre. Moreover, PLP's strategy includes a close monitoring program in every local collection point (citizen clusters) in order to capture information and learn the local patterns of waste disposal and separation, and customise the system accordingly. This paradigm change in the organisation of the network represents a creative breakthrough qualitatively different from the average strategy proposals; it is visually illustrated in Figure 2.



(a) (b)

Figure 2 A paradigm change from the system state today (a) to the new proposal (b) presented by team PLP in group DIU where the network of waste collection and recovery in the city is reorganised, transforming the values and dynamics of nodes, and enabling local customisation.s

In contrast, team LLJ of group DNU01 presented mostly SL ideas, and received a low quality score. This team's strategy includes the privatisation of the garbage collection process, salary raises for employees and subsidies for private companies with money from the recycling of materials. The strategy also incorporates an ambiguous system of garbage-management bonds that citizens earn as they comply with waste separation and disposal laws. While these ideas are not without good potential, they received SL tags because they address low-level leverage points of the system, and they earned low quality scores because they remain unconnected, ambiguous and lack details that demonstrate deep reasoning beyond trite stereotypes.

These two cases are exemplary of clear association of thinking style with quality of proposal, but in other cases this relation is not as straightforward, as discussed above.

Discussion

This study demonstrates that the set of methods and tools currently used in some of our courses are valuable tools for promoting systemic thinking in our students. These activities may vary in their objectives, scope, and implementation (as summarised in section 3.2.2), but they all address the deep understanding and purposeful intervention in highly complex systems. More precise studies are necessary to characterise the role of each activity type and their applicability in different disciplinary and teaching situations.

Evidence is also provided to suggest that regarding systemic reasoning, the distinctions between disciplinary and multi-disciplinary teamwork may be weaker than what was expected. No doubt, multi-disciplinary work has clear advantages and merits, but at least in the type of conditions and issues addressed here, its impact on high-order systemic thinking seems rather limited. This could mean that systemic thinking need not be constrained to multi-disciplinary settings, as intuitively assumed. An important implication of high-order systemic thinking as a cross-disciplinary skill, is that all disciplinary courses may be suitable for nurturing systemic thinking.

This somewhat unexpected outcome regarding multi-disciplinary teams may point towards other possible moderator variables at work. For instance, the creativeness and innovation of teamwork dynamics has been associated with the strength of social ties [26] and other variables related to culture [29, 30].

Furthermore, diagnosing systemic thinking in a team or a person would remain largely irrelevant if this type of reasoning failed to produce more creative and higher quality responses. Our study confirms the premise that teams with high-order systemic thinking consistently yield high-quality and original solutions. This is a promising outcome that validates this type of research initiatives, and motivates more specific questions for future work.

The research presented in this paper reinforces the claim that the design of sustainable products, services and systems could significantly benefit by the development and enactment of systemic thinking. This could be achieved by gearing teaching interventions across disciplines towards identifying, understanding and intervening complex systems. It is in this context that the buzzword 'design thinking' seems limited and inaccurate. What is necessary in design as in other disciplines, is 'to design our thinking' in a more systemic level.

Future steps

Further studies are required to characterise and develop 'systemic toolkits' to intervene courses across disciplines and at different scales: sessions, terms, semesters, etc. It is difficult to measure the potential of every learning intervention tool due to their varying nature, scope and time periods of applicability. However, such toolkits could provide cross-disciplinary teaching instruments to explore given the particular conditions at hand.

The assessment exercise presented here may require further exploration in terms of the topics covered, the length of activity, the team formation strategies used, and other potential moderator variables. The authors plan to replicate this study in future semesters in order to validate its predictive utility.

The analysis of the team responses could be revised and extended. The three-tier framework of systems thinking could be refined into more specific categories and responses could be contrasted against individual competencies before and after the test. The criteria of quality and originality could be validated against third-party evaluations by incorporating independent judging panels in the evaluation and categorisation of responses.

Finally, this work could lead to valuable input for curriculum design projects. Guidelines could be developed to incorporate teaching interventions throughout undergraduate and postgraduate programs across disciplines.

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