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Considering Student Retention as a complex system: A possible way forward for enhancing Student Retention.

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Abstract

This study uses Multilayer Minimum Spanning Tree analysis to develop a model for student retention from a complex system perspective, using data obtained from first year engineering students at a large well-regarded institution in the EU. The results show that the elements of the system of student retention are related to one another through a network of links and that some of these links were found to be strongly persistent across different scales (group sizes). The links were also seen to group together in different clusters of strongly related elements. Links between elements across a wide range of these clusters would have system-wide influence. It was found that there were no links that are both persistent and system-wide. This complex system view of student retention explains why actions to enhance student retention aimed at single elements in the system have had such limited impact. This study therefore points to the need for a more system-wide approach to enhancing student retention.

Keywords: Higher Education, Student Retention, Complex Systems, Multilayer Minimum Spanning Tree Analysis

1 Introduction

Too often interventions in higher education aimed at improving student retention do not appear to achieve their desired outcomes. This is particularly true in engineering education where student retention is an ongoing area of challenge (e.g., Committee on Science, Engineering, and Public Policy, 2007; European Commission, 2004). Both educationists and industrialists have argued that part of the problem lies in treating educational situations in a linear way, whereas they are really complex systems (Stermann, 1994; Davis & Sumara, 2006; Morrison, 2008; Forsman, et al. 2012; Stephens & Richey, 2013). Although, why a comprehensive complex systems analysis is feasible and how it is possible has been illustrated (Forsman, *et al.* 2012), the kind of in-depth analysis described in this article has not been presented in the literature before.

Our aim in this article is to show how an implementation of a Multilayer Minimum Spanning Tree (MMST) analysis can be used to generate a useful representation of the complex system of student retention for local interpretation and consequent action, and to illustrate the limitation-to-action insights that can emerge from such an analysis. This is achieved by incorporating two common structural features of complex systems – the networked structure, and nestedness – into the analysis for a large set of data collected at a well-regarded EU university. To guide the interpretation, we draw on Schön's (1983) work, which introduced the usage of a 'virtual world' in professional decision making.

We express these goals in the following research questions:

- 1) *How can the complex system of an educational situation be represented by framing it in terms of its networked structure and nestedness?*
- 2) *How can the representation created in this way be used in order to inform decisions regarding enhancing student retention?*

2 Background

2.1 Student Retention

The issue of effectively enhancing the retention of engineering students has become critically important in many parts of the world. This is because the demand for competent engineers has been exceeding availability for some time (European Commission, 2004; Committee on Science, Engineering, and Public Policy, 2007). Most of the research aimed towards improving student retention has drawn on the Student Integration Model, SIM (Tinto 1975; 1987) and the Student Attrition Model, SAM (Bean 1980; 1982).

The theoretical framing for the SIM and SAM models and their derivatives have been refined through localized empirical trials for many years (Tinto, 1975; Braxton, 2000; Metz, 2004). Institutional action in terms of enhancing student retention has not had a lasting and significant impact in any particular context that we know of (European Commission, 2004; Committee on Science, Engineering, and Public Policy, 2007; Tinto, 2012). Van den Bogaard concluded that the SIM and SAM models do not provide a “definite understanding of the problem: none of the models, when used fully, explains why some students drop out and others do not.” (Van den Bogaard, 2012: 71).

However, the previous work in student persistence has yielded extensive insight into the processes affecting student retention. Van den Bogaard (2012) summarised the groups of factors that impact student retention: student background variables, student disposition variables (which are subject to change over time), student behaviour, elements of the social and educational environment, and external factors.

Forsman, *et al.* (2012) demonstrated that student retention has the characteristics of a complex system. This work dealt with the *networked structure* and *nestedness* of

complex systems through two different analytical methods. In what follows, we describe a single method to elucidate these characteristics and explore the insights that this new framework provides.

2.2 Complexity in Education

Complex systems are made up of many interconnected elements. Complex systems are characterised by properties such as self-organization, nestedness and emergence, with the individual elements having agency (i.e., the ability to respond to stimuli in different ways). An emergent property, or behaviour, of the system cannot be simply inferred from the properties or behaviour of the constituent parts. The nesting can also be with respect to different levels (or scales), as well as across groupings at the same level. The relationships between elements, whether on the same level or on different levels, may range from being more ordered and predictable to being less ordered and predictable (Davis and Sumar, 2006). Further, inference of causality in these systems is often problematic due to the diverse interactions between multiple elements on different levels of the complex system (Morrison, 2008; Miller & Page, 2007).

2.3 Complexity Thinking

Davis & Sumara (2006) introduced *complexity thinking* into the analysis of educational systems. In this framework, cause and effect are thought of as emergent properties of processes of complex systems, compared to linear thinking, where it is uncritically and implicitly assumed that there are direct cause and effect relationships between the elements of the system. This framing amounts to a *paradigm shift* in how the educational process is viewed. Complexity thinking is not characterized by a particular method, but draws on the use of tools, analogies, and metaphors used in the study of complex systems.

A number of researchers in education in the STEM disciplines have adopted this approach (Lemke & Sabelli, 2008; Morrison, 2008; Stephens & Richey, 2013). Some important questions arise concerning how, in an educational setting, to apply the core concepts of a complexity framework, such as agent interaction, self-organization, nestedness, networked nature, feedback, and emergence (Davis & Sumara, 2006; Jacobson & Wilensky, 2006; Lemke & Sabelli, 2008; Stephens & Richey, 2013).

2.3.1 Nestedness

Educational processes have been characterized as being composed of nested systems and sub-systems (Davis & Sumara, 2006; Forsman, *et al.*, 2012). In this article we will examine one particular complex system characteristic in relation to student retention, namely *nestedness*. We especially examine nestedness in terms of two different dimensions, namely *vertical* and *horizontal* (cf. Lemke, 2010).

Vertical nestedness refers to different levels/scales with regard to size (Davis & Simmt, 2006). We characterize *vertical nestedness* in terms of students being nested within academic and social groups, then in classes, departments, and schools, and finally in the university as a whole, which in turn is nested within the society around it. Moreover, the (sub)systems can be also seen as operating on multiple scales regarding time (for example, the process of student retention usually takes less time than the development of new policies).

The notion of nestedness can also be viewed from a “side-view” (i.e., *horizontal nestedness*): each nested level is made up of a range of diverse clusters of constituent parts: students are diverse, the academic and social groups are diverse, and not all social and academic groups reside in only one classroom, nor only one department, or even within one university.

The nestedness of complex systems brings us to argue that depending on which level of this nested system (for example the student level, or the classroom level) we choose to study, we might find different rationales and explanations for student retention. This realization is echoed in the turn-over research field where Hausknecht, et al. (2011) argued that it is not valid to assume a one-to-one relationship between effects on the individual level to the collective level. Thus, the assumption of a one-to-one relationship between previously identified critical elements related to student retention and their function at different nested levels needs to be explicitly explored.

The design and implementation of strategies in complex systems is problematic as a result of the multiple temporal and spatial scales the systems and sub-systems operate on (Sterman, 1994). In particular, the time delay between implementation of action and feedback from the system is probably the most important constraint to learning about complex systems (Sterman, 1994; Rahmandad, Repenning, & Sterman, 2009). This applies especially to the system of student retention, where the effect of implementing institutional action that enhances student retention has a time delay of months, or even years. Even when assuming neither distortion nor error in the feedback from the system (Rahmandad, Repenning, & Sterman, 2009), after the times required for effects to be observed, it is possible – and likely – that many elements of the system, such the particular students and lecturers will have changed.

If there is *scale variance*, as argued by Morrison (2008), we deduce that there must be *scale invariance* within complex systems. In our study it was important to identify elements which are scale invariant (i.e. *stable* across the different vertical nested levels of the system). These stable elements would be more suitable as targets for institutional action, as the relationships are more stable than others across the different levels of the system. While the concept of the stability of elements across different

levels of a complex system is new in educational research, it is not new in the study of human-environment complex systems (cf., Davis and Sumara, 2006; Manson, 2008).

2.4 *The use of a Virtual World*

Stephens and Richey (2013: 421) argue that research aimed towards better understanding of education as a complex system must be aimed at exploring empirical methods for analysing complex systems. In addition Rahmandad, Repenning, & Sterman (2009), Sterman (1994), and Davis & Sumara (2006) state that to learn about such complex systems and their dynamics, it is critical to initiate, or simulate action in such a system and collect the feedback from this system.

To combat the problems associated with working with complex systems in real time, Sterman (1994) put forward the usage of Schön's *virtual world*, which makes it possible for practitioners to “manage some of the constraints to hypothesis-testing experiment which are inherent in the world” (Schön, 1983: 157). As an example of the use of a virtual world, Schön (1983) describes an architect working with a drawn world (which we might call a *representative model* of a virtual world):

Some variables which are interlocking in the build world can be separated from one another in the world of the drawing ... a building shape can be considered while deferring the question of the material from which the shape is to be made.... As an architect's practice enables him to move back and forth between drawing and building, he learns how his drawings will “build” and develops a capacity for accurate rehearsal. He learns, for example, how drawings fail to capture qualities of materials, surfaces, and technologies. ...Drawing functions as a context for experiment precisely because it enables the designer to eliminate features of the real-world situations... but when he comes to interpret the results of his experiments, he must remember the factors that have been eliminated. (Schön, 1983: 158-159).

Sterman (1994) describes this as a recursive and adaptive process where the virtual world provides immediate feedback of actions in the system, in a way that is highly constrained or impossible in the real system. Use of a virtual world also provides a platform for experimentation (Sterman, 1994). Sterman (1994) argues that knowledge of the critical elements of the complex system and the relationship between them are essential to know what might be manipulated in the complex system and what the possible outcomes might be. Thus, we envisage developing a visualization of the system of student retention, which can be used as a representative model for the virtual world of student retention made up of the critical aspects of the system and how they relate to one another. This will enable us to explore possible actions for improving student retention and what their impact might be.

3 Methodology

A detailed description of the methodology employed in this study is given in Appendix

1. What follows is a description of the key features of the methodology needed to understanding and interpreting the results obtained.

We used the characteristics of a Multilayer Minimum Spanning Tree (MMST) as the analytical tool to generate the representative model of the system of student retention under consideration. The MMST is built up from a large enough series of MSTs, with each MST consisting of a randomly sized and randomly chosen set of students. MMST uses many randomly-sized groups of students, rather than presuming links between particular students due to their pre-defined characteristics.

In order to ensure that the MMST is a good representation of the system, it needs to be built up from a large-enough number of MSTs to ensure the significance of the links obtained. It also identifies both positive and negative edge-weights.

Randomisation is used to prevent ordering bias. There is also a need to distinguish between rare connections and random connections (noise). The stability of the link between particular elements is then the number of connections between these elements over the whole set of MSTs.

What we need to identify in the MMST is how persistent each element in the system is, as well as how strong the system-wide influence of each element is.

Appendix 1 describes persistence (vertical nestedness) in terms of the concept of topological diversity, and system-wide influence (horizontal nestedness) in terms of the concept of cluster diversity. Both of these concepts are adapted from the study of social diversity. If a particular element of the representative model has stable relationships with other elements (i.e., it is persistent), but has very limited potential for system-wide influence (i.e., its potential influence is highly localised), different targets for institutional action may be more suitable.

Topological diversity is a measure of the distribution of frequencies with which a particular individual's response connects to other individuals' responses: low topological diversity indicates connections with a wide range of other individual's responses, whereas high topological diversity indicates connections with only a few other individual's responses. Low topological diversity therefore represents stability of an element across the whole range of different group sizes, which is scale invariance. Topological diversity is characterised by the distribution of edge-weights (links) between each element and all the other elements in the system.

Cluster diversity is a measure of the frequency with which a particular individual's response connects with other individuals' responses in different clusters outside the cluster where the individual's response belongs. Clusters are first defined by using a walk-trap algorithm to select groups of elements which have particularly strong

relationships with one another. Low cluster diversity is then a measure indicating that an element primarily has links only with elements in the same cluster, whereas high cluster diversity indicates that an element has many links with elements outside its own cluster as well as within its cluster. High cluster diversity therefore represents system-wide influence.

The data used in this analysis was obtained from a sample of 573 first year engineering students at a highly respected European university. They each filled out a questionnaire of 79 questions. This data was supplemented by demographic and academic data from the institution's database. The element representing students' credits achieved has been used as a proxy for retention (Tinto, 1987).

4 Results

This section is divided into two sub-sections, each corresponding to one of the research questions. The first sub-section covers the estimation of the uncertainty of the networked model. The second sub-section first presents the necessary steps required to characterize possibilities for institutional action through visualization of the representation developed, thus creating a representative model for the virtual world of student retention. Secondly, this sub-section analyses possible constraints to institutional action aimed at enhancing student retention, based on the representative model.

4.1 Multilayer minimum spanning tree analysis

The first step in developing a valid model of the system was to determine an estimate of the uncertainty in the creation of the MMST. The size of each subset in each MST is drawn from the whole population randomly and contains between 85 and 584 students.

The estimation of the uncertainty was based on creating multiple pairs of MMSTs, each time doubling the number of MSTs constituting them. We did this by calculating the mean difference of the edge weights and the standard deviation in the edge weights for the pair of MMSTs and found that this decreased when increasing the number of MSTs in each MMST (see Figure 1). Both the mean uncertainty of the differences in edge weights between the pairs of MMSTs, and the standard deviation of the estimated uncertainty fell below 5% after an aggregation of 65 536 MST, so that number of MSTs was used in the MMST to represent the complex system.

Figure 1: The estimated uncertainty between edge weights and the standard deviation between pairs of aggregated MMSTs. The y-axis is the mean difference between the weights of identical edges. The x-axis is number of MSTs created to form the MMSTs.

4.2 Developing the representative model of the virtual world

4.2.1 Topological Diversity

Shows the distribution of topological diversity, illustrating the range of scale variance for the elements of the system. This is the first time the diversity in the different levels of a complex system is examined in this way. There is a broad range of elements with medium topological diversity, quite a few elements with lowish topological diversity, and a small number of elements with highish topological diversity (see Figure 1). Table 1 gives both the topological diversity and the cluster diversity for each element to get a sense of what kinds of elements have high and low topological diversity. The elements in Table 1 are arranged in order of increasing topological diversity.

Figure 2: Histogram of the distribution of the measured topological diversity for all elements.

Table 1: Calculated Topological Diversity and Cluster Diversity for each element in the representative model.

Element	Topological Diversity	Cluster Diversity	Element	Topological Diversity	Cluster Diversity
Students' self-evaluated skills [Skill_comp]	0.284	0.185	Teacher behaviours [Tc_enthusiasm]	0.469	0.394
Scheduling [N_courses]	0.298	0.421	Student's credits achieved [P_EC_N]	0.472	0.550
University facilities [Fc_studyF]	0.313	0.157	Students' study behaviour [Sb_syst]	0.473	0.277
Students' study behaviour [Sb_exam]	0.314	0.178	Students' previous achievement in mathematics [SE_math]	0.475	0.153
Teacher expectations [Expec_diff]	0.316	0.203	Assessment and feedback [Ts_level]	0.476	0.511
Language skills [Language_Eng]	0.337	0.258	Course materials [Oo_feedback]	0.481	0.530
Assessment and feedback [Ts_trans]	0.347	0.187	Stem profile combination [B_Ment_profile]	0.483	0.618
Travelttime total	0.348	0.141	Students' study behaviour [Sb_mark]	0.488	0.520
Fraternity membership [Member_frat]	0.353	0.327	Teacher behaviours [Tc_explain]	0.488	0.222
Teacher behaviours [Tc_available]	0.368	0.302	Students' study behaviour [Sb_bursts]	0.490	0.447
Students' study behaviour [Sb_eff]	0.380	0.343	Scheduling [N_travel_days]	0.493	0.665
Course materials [Oo_late]	0.383	0.489	Course materials [Oo_material]	0.493	0.446
Teacher behaviours [Tc_master]	0.383	0.202	Students' self-evaluated skills [Skill_physics]	0.499	0.489
Students' study behaviour [Sb_deepl1]	0.385	0.386	Students' study behaviour [Sb_check]	0.501	0.437
Scheduling [N_lectures]	0.388	0.456	Students' study behaviour [Sb_keepup]	0.501	0.394
University facilities [Fc_tcmn]	0.393	0.267	Course materials [Oo_spread]	0.501	0.519
Language skills [Language_Dutch]	0.393	0.395	Teacher expectations [Expec_interest]	0.503	0.508
Students' study behaviour [Sb_toomuch]	0.393	0.148	Students' study behaviour [Sb_deepl2]	0.506	0.375
Assessment and feedback [Ts_feedback]	0.395	0.214	Students' study behaviour [Sb_forget]	0.514	0.686
University facilities [Fc_studyC]	0.398	0.431	Students' study behaviour [Sb_goal]	0.516	0.388
Assessment and feedback [Ts_consist]	0.404	0.345	Students' study behaviour [Sb_pause]	0.518	0.432
Students' Age [Age]	0.405	0.272	Students' previous physics achievement [SE_physics]	0.518	0.419
University facilities [Fc_relax]	0.408	0.288	Scheduling [N_exams]	0.518	0.611
Assessment and feedback [Ts_proj]	0.409	0.438	Students' study behaviour [Sb_hard]	0.518	0.365

Scheduling [N_mandatory]	0.413	0.318	Students' study behaviour [Sb_tempo]	0.519	0.170
Assessment and feedback [Ts_time]	0.419	0.524	Scheduling [N_active]	0.520	0.721
University facilities [Fc_studsup]	0.424	0.669	Teacher expectations [Expec_BSA]	0.524	0.617
Students' Housing situation [Housingsituation]	0.437	0.322	Students' self-evaluated skills [Skill_math]	0.525	0.531
Teacher behaviours [Tc_empathize]	0.437	0.164	Teacher behaviours [Tc_content]	0.525	0.435
Students' Parents' education [Ed_parents]	0.438	0.387	Assessment and feedback [Ts_exp]	0.528	0.398
Assessment and feedback [Ts_constr]	0.441	0.338	University facilities [Fc_atm]	0.535	0.580
Students' impairments [Imp_N_total]	0.443	0.473	Students' study behaviour [Sb_help]	0.565	0.654
Students' biological gender [Gender]	0.448	0.469	Students' study behaviour [Sb_enough]	0.568	0.562
Degree importance [Important_Delft]	0.451	0.461	Assessment and feedback [Ts_repres]	0.579	0.523
Course materials [Oo_book]	0.452	0.322	University facilities [Fc_stmen]	0.589	0.692
Teacher behaviours [Tc_hall]	0.459	0.323	Students' study behaviour [Sb_behind]	0.591	0.542
Course materials [Oo_courses]	0.461	0.597	Students' prior education [Prior_ed]	0.598	0.587
Students' study behaviour [Sb_concen]	0.466	0.332	Students' study behaviour [Sb_prep]	0.639	0.683
Degree importance [Important_P]	0.468	0.447	Students' prior exposure to university PR [PR_total]	0.652	0.799

In order to interpret the results shown in Table 1, note that high topological diversity represents elements that functioning differently at different nested levels of the system, and low topological diversity represent elements that function the same across all nested levels (i.e. are scale invariant).

The five elements with the lowest topological diversity are: self rating of computer skills, number of courses, availability of working places to study, studying mainly for tests, and whether the programme of study was as difficult as the student expected (i.e. these elements are the same for most students). The five elements with the highest topological diversity are: exposure to PR activities, whether students prepare differently after a failed exam, prior education, always being behind in their work, and access to a student mentor (i.e. these elements vary for most students). To be able to identify significance in these results the cluster diversity first needs to be presented.

4.2.2 Cluster Diversity

The calculated cluster diversity of each element is also presented in Table 1, using the clusters found in the following section. Elements with high cluster diversity relate to multiple clusters and are likely to have system-wide influence, whereas elements with low cluster diversity relate largely within their own cluster and are not likely to have system-wide influence. To investigate the relationship between cluster diversity and topological diversity we plot them against each other, as shown in

Figure 3: Plot of topological diversity vs. cluster diversity. The line is the best fit regression line.

The best candidate for institutional action would be an element that is stable (i.e. has low topological diversity) *and also* has system-wide influence (i.e. has high cluster diversity). Examination of Figure 3 reveals *that there are no elements that fall into this category*. Figure 3 also shows that cluster diversity and topological diversity in this representation are positively correlated. We postulate that this tends to indicate that a constraint for effective institutional action with regard to enhancing student retention is that choosing targets for institutional action is a trade-off between the elements with

high cluster diversity (and thus a strong possibility for global system effects) and elements with low topological diversity (and are thus scale invariant, having an effect, but mostly within local clusters in the system). It would appear from these results of this analysis that you cannot have both.

4.2.3 Visualization of the network connections

Figure 4a-d shows the links between the elements in the system, and thus the structure of the representative model. The thick links represent the stable structures, i.e., connections that are frequently found in most sub-sets of the data, and the weak links represent the unstable structures, i.e., the connections that are found infrequently in the sub-sets of the data. The size of each element in Figure 4 is the inverse topological diversity of that element, so large size represents low topological diversity (highly stable/scale invariance) and small size represents high topological diversity (low stability). We have chosen to visualize it as such, as Schön (1983) argues that visualisation of a model of a virtual world must be done so as to show how much of the information has been eliminated from the visualization.

In Figure 4a, most edges that were detected are shown, and the small sized elements show a wide range of connectedness to other elements, and the large elements show strong links to a few other elements. In Figure 4b, more of the unstable edges are hidden but the size of the elements are the same (their topological diversity does not change), and similarly for Figure 4c, and Figure 4d, where most unstable edges are not shown. It should be noted that the ‘small’ elements have a large number of unstable edges, but it is difficult to see the links of these unstable edges. Thus, most information is still captured by the illustration in Figure 4d, in terms of the range of stable and unstable relationships for each element.

Figure 4: Visualization of the MMST of the aggregated 65 536 MSTs. The widths of the links represent how stable the links are, with thicker lines indicating more stability in the structure. Grey links are positive edge weights and red links are negative edge weights. The size of the elements represents the inverse topological diversity, where large elements have low topological diversity and small elements have high topological diversity. The four visualizations have removed the a) 1% , b) 5% , c) 10%, and d) 15% lowest edge weights. The colours represent clusters as identified by the infomap

algorithm (Rosvall & Bergström, 2008). A full description of all the elements is given in Appendix 2.

5 Discussion

The work presented in this article is a part of on-going research which deals with visualizing, and understanding educational processes, such as student retention, as a complex system. The discussion is in two parts, each corresponding to the two research question stated in the introduction.

5.1 *The creation of a networked system*

The research question concerns how the networked nature and nestedness of critical elements of student retention be detected and visualized. To answer the first research question, we introduced MMST analysis as a method of detecting links between different elements and thus created a networked model of the critical elements of student retention (as identified by previous research). This demonstrated that the networked nature and nestedness of a complex system could be explored through one methodology.

Although this method of creating networks of correlated data was originally intended to be used on a far greater sample size in analysing co-expression networks (Grönlund, Bhalerao, & Karlsson, 2008), it is important to note that this article is an illustrative step forward in conceptualizing student retention from a complexity thinking perspective.

This methodology is dependent on correlation statistics, which is not evidence for causality (e.g., Davis, 2003). The links *only* show the strengths of the relationships between different sets of elements. Thus, the inference of causality, identified as being

particularly problematic in modelling complex systems, remains problematic. This is despite having identified the interconnections between the elements on different levels of the complex system, which is argued to be the foundational problem of inferring causality in complex systems (Morrison, 2008; Miller & Page, 2007). What this analysis cannot show is whether or not a pair of elements are positively related at one level, but negatively related at another level (cf. Hausknecht, et al., 2011). High scale variance of elements only *hints* that these elements might relate differently across the different levels of the system.

The creation of a representative model can be seen as problematic because the current state of the methodology is more descriptive than predictive. However, the descriptive illustration of the connectedness of critical elements of student retention can serve as a representative model for a virtual world whereby it becomes possible to extend the understanding of student retention as a complex system.

5.2 *Where does this leave us?*

This study, through the developed representative model of the virtual world of student retention, affords the possibility of exploring potential institutional actions to enhance student retention. Thus it provides a basis for discussion of proposed general and localized possible targets of institutional action that engages practitioners in what Schön (1983) calls *reflective conversation with the situation*. In order to understand possible effects of interventions, practitioners can actively engage with this representative model of the virtual world, by interrogating the different parts of the system, and their relationships with one another. In this way they may be able to learn something about the complex system involved (Sternan, 1994).

The visualization created shows that critical aspects of student retention (as previously identified by the field [Appendix 2]) are interlinked, and offers the possibility to postulate what the outcome of a particular action might be. An element of student retention can be chosen to be change, and the links then afford what (and in what way) interlinked elements are likely to be affected, noting that the further away elements are, the more uncertain the effects on that (or of that) element will be.

While such a visualization can help with deciding what impact institutional actions might have, Sterman (1994) stresses that the use of virtual worlds still can be problematic when actions are implemented. This is due to possible implementation failure, or “game playing” (agents within the system following private agendas or local incentives). The only way of seeing how the proposed changes actually fare, is to implement them and wait for feedback from the system.

In illustrating the constraints of institutional action aimed at enhancing student retention, the analysis undertaken in this article implies that choosing institutional action is a trade-off between possibilities for system-wide influence and persistence across different scales. This implication from our results is echoed in the field of complex system analysis, as captured by Hollis (2001) in an article analysing sustainable dynamic systems:

“All of these indicators and all of the attributes make sense. The problem is not that they are wrong, or that they are not useful. They are, if anything, incomplete. Rather, they suggest a complexity that can overwhelm understanding, even when, in specific situations, only a subset of these entities are relevant.” (p.390)

That is, in order to enhance student retention from a complexity system perspective, it would appear that it may be necessary to target multiple elements of the system, many of which may be beyond the reach of change without a system-wide perturbation.

What this study of student retention from a complexity perspective has therefore uncovered is that any action aimed at only a single element of the system of student retention is unlikely to have a significant impact on student retention. This explains why efforts at enhancing student retention have so far had such limited success, and points to the need for a much wider-ranging set of actions in the light of the links found between the elements of the system of student retention.

6 Acknowledgements

-Intentionally left blank, as this is the final thing that is added-

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Appendix 1: Detailed methodology

For our purpose of creating a representative model of a ‘virtual world’ of student retention, we build our analytic approach based on complexity thinking (e.g., Davis and Sumara, 2006; Manson, 2008), student retention research (e.g., Bean 1980; 1982; Braxton, 2000; Metz, 2004; Summerskill, 1962; Tinto, 1975; 1987), network theory (e.g., Newman, 2010), and an implementation of a MMST analysis (cf. Grönlund, Bhalerao, & Karlsson, 2008).

This methodology and our theoretical framework make it possible to characterize different critical elements of student retention as more scale invariant than other elements- i.e., *as more stable across the vertical nestedness of the complex system*. However, the stability of these critical elements also needs to be explored in relation to their potential to have system-wide influence- i.e., *both have effects throughout the horizontal and vertical nestedness of the complex system*.

Network Theory

In the analysis of our system, we draw on the tools available from network theory (c.f., Newman, 2010) to analyse the networked structure of the elements and their edge weights (i.e., how strong the connections between elements are).

In network theory, a network typically consists of elements (cf. *nodes* or *vertices* Newman, 2010) and edges. The elements are the components of a system, and the edges represent the relationships (links/connections) between the elements. The strength of the connection between two elements is denoted as the *edge weight*. A minimum spanning tree is a connected undirected network with as few links as possible, such that there are no loops (i.e., there exists only one path between each element pair) in that network, and the distance between each element pair of the tree is minimized (i.e., the value of the sum of edge weights is minimized, so that the correlations between all elements are maximised). No loops in each of the individual MSTs does not mean that the aggregated MMST has no loops.

In a network, there are groups of elements that are more connected to each other than to the rest of the network. Detection and characterization of these groups of elements (which we call clusters) can be done in a number of ways (cf. Newman, 2010). In this study we have chosen to use the infomap community detection algorithm (Rosvall & Bergström, 2008). The infomap algorithm (Rosvall & Bergström, 2008) is based on the walk-trap algorithm (Pons & Latapy, 2005), in which the main idea is that a random walker placed at a random position (node) in the network will get “trapped” within a cluster in the network. The infomap algorithm optimizes the number of steps the random walker needs to take in order to find a community structure. The random walker placed by the algorithm steps through adjacent elements in relation to the strengths of the edge weights. Therefore, it is likely that the random walker follows high value edge weights and therefore tends to get “trapped” in strongly linked clusters in the network.

Data gathering

Our data was collected in the fall of 2010 at a highly regarded university in the European Union, which offers 3-year bachelor degrees for a wide variety of engineering and science programmes. We studied a cohort of first-year engineering student using an online questionnaire that was made available to all the students in this cohort; the response rate for this questionnaire was 25% (573 of 2292). This questionnaire was built up from the literature on student retention (Van den Bogaard, 2012), largely based on the SIM and SAM models. The questionnaire also included questions that were selected based on interviews with a selection of first year students at the same university. In total, the questionnaire was made up of 79 questions. The dataset was combined with data taken from the central student administration and from the curriculum and programme structures at this university. The items in the questionnaire and rationale behind the development of the questionnaire are listed in Appendix 2.

The survey contained questions regarding students’ backgrounds (such as parental level of education), social and academic integration (such as union membership), academic

confidence (such as self-reported confidence of skill in maths and science), motives (such as job prospects), and commitment (such as staying at that university). Furthermore, the survey also contained questions regarding student study behaviour (such as a deep approach to learning) and on the students' perceptions of the educational climate (which was operationalized in four topics: perceptions of teachers, assessment, facilities, and curriculum organisation).

Multilayer minimum spanning tree (MMST) analysis

Our implementation of MMST analysis simulates a range of possible sub-sets of the students surveyed while not “forcing” them into any particular group constellations or group sizes (cf. *bootstrap*, Davison, 1997). A critique of this approach could be that such sub-sets of the collective will not necessarily have the kinds of specific social bonds or academic attachments that have been argued to be of importance for student retention in other studies (for example, see Thomas, 2000; Sacerdote, 2001). We suggest that these randomly generated sub-sets of the entire collective act as a proxy for the range of social and academic sub-groups that might exist within, for example, classrooms or departments.

Our modelling effort creates a networked representation of elements which are influencing the process of student retention using the correlations between measured elements in randomly chosen sub-sets of the data set. These correlations are used to create a multilayer network generated from minimum spanning trees (MSTs). The links in the MSTs represent the strongest Spearman correlation (Spearman, 1910) based on the sample of random sized random sub-sets of the data and are created through the use of Prims' algorithm (1957). The edge weights of the links in the aggregated MMST between elements are the frequency of how many of the MSTs contain that edge/connection.

To ensure that each link is significant in the creation of the MMST, a degree – degree correlation analysis is applied in the network analysis (Sneppen & Maslov, 2002). Such an analysis is normally applied to much larger networks. In the analysis undertaken we only kept links in each MST which corresponded to correlations with significances $p \leq 0.01$, which would

then ensure suitable links within the network. This is interpreted as the probability for the null-hypothesis is 1%.

Edges can be both positive and negative in the MMST to illustrate if it was the strongest positive or negative relationship between elements that was estimated. To do this, we keep track of the positive and negative correlations in each subset, and correspondingly assigned negative or positive edge weights to the edges in the MSTs constituting the MMST. Note that this is a result of characterising the values that each element can take over a range from -1 to +1.

Further, our implementation randomizes the top two strongest correlations in each subset by alternating between them in the creation of links, in order to take into account the possibility that our data is “noisier” than the data used in the original article. This approach also overcomes ordering bias, and, together with the forced significance in each MST, allows for detection of ‘weaker’ links in the networked system. Including links that appear in a few of the generated MSTs increases the information quality of the network (Grönlund, Bhalerao, and Karlsson, 2008). Thus a link in the created MMST is ‘weak’ because it reflects rare signalling events rather than merely connectedness based on chance.

Our use of MMSTs also shows how identification of the connectedness of the concepts measured can be established across different nested levels. Because the implemented method explores different sized random sub-sets of the population, the ensuing representative model of a ‘virtual world’ displays similarities and differences across different levels of the university (as described in the section on complexity thinking). Varying the number of students in the analysis thus accounts for the different groupings within the context of the university (social or academic grouping, classroom, course, department).

Creating a representative model for a ‘virtual world’

The representative model of the interconnectedness of critical elements of student retention is achieved by using three concepts: stable structures (to characterize the frequent links between elements), topological diversity (to characterize the scale invariance of particular elements), and

cluster diversity (to characterize the possibility of each element for system-wide effects).

Stable structures

From the above description of the MMST analysis method, we define *stability of an edge* in the network as being the absolute value of the edge weight connecting two measured elements, which related to the number of times that relationship is the strongest relationship in the bootstrapped MSTs.

Topological Diversity

The edges in the MMSTs show a range of stability; some are very stable and are reproduced in most sub-sets, others are particular and have a low frequency of connections with any other elements of the system. However, the stability of an edge does not explicitly indicate what elements could potentially be *scale invariant* and to what extent these elements are not. In order to identify and visualize the tendency of scale invariance of an element, a calculation of *topological diversity* was carried out, which is based on Eagle, Macy, and Claxton's (2010) concept and determination of *social diversity*.

Computationally, topological diversity describes how much information is required to describe a particular element in relation to how many edges connect that element to other elements and the distribution of those edge weights. Analytically, as shown in Equation 2, the topological diversity D_{top} is related to the Shannon Entropy ($P_{ij} \log(P_{ij})$) [Shannon, 1948]) of element i , and is normalized by the number of i 's links (k).

$$D_{top}(i) = \frac{-\sum_{j=1}^k P_{ij} \log(P_{ij})}{\log(k)}, \quad \text{Eq.2}$$

where P_{ij} is the proportion of the total edge weight that is distributed to each of i 's links to other elements. As an example, if an element has two links with equal edge weights to two other elements, it has a lower topological diversity than if the two edge weights were different. An element has very high topological diversity when it is connected differently with many other

elements. Thus, we argue that topological diversity characterizes to what extent the measured element relates differently over the levels of the nested complex system, i.e., it is a characterization of the scale variance of the measured elements. The inverse of D_{top} is then a characterization of the extent to which a particular element is scale invariant.

Topological diversity was originally a measure of people's phone usage (cf. Eagle, Macy and Claxton, 2010). The topological diversity score represents how many people a given person calls, and the frequency of those calls. If one person calls only one other person all of the traffic volume is to one person, that person has a low diversity score. On the other hand, if one person calls a number of people and calls each of those people with different frequency, that person has a high diversity score.

Cluster Diversity

Cluster diversity helps characterize each element's possible maximum spread *in the system*. In conceptual terms, this means that the vertical levels of the system are 'collapsed' into one in order to identify clusters of elements *while at the same time retaining the information of the scale invariance of each element*; the clusters represent the 'collective' horizontal nestedness across all vertical levels. We do this in order to identify elements that both are likely to be scale invariant, and have links to more than one cluster.

As with topological diversity, cluster diversity is based on social diversity (Eagle, Macy, and Claxton, 2010). In calculating cluster diversity, P_{ic} (from Eq. 3) is the edge weight between the element i and the cluster c :

$$D_{clu}(i) = \frac{-\sum_{j=1}^k P_{ic} \log(P_{ic})}{\log(k_c)} \quad \text{Eq.3}$$

The sum of the Shannon entropy ($P_{ic} \log(P_{ic})$ [Shannon, 1948]) for the distribution over all elements and all clusters is divided by the logarithm of the number of clusters identified (k_c) by the infomap algorithm for community detection (Rosvall & Bergström, 2008).

Cluster diversity was originally a measure of people phone usage in terms of area codes (Eagle, Macy and Claxton, 2010). If a person only calls other persons within the same area code, then the volume of that person's traffic is directed towards one area code, and that person has a low cluster diversity score. On the other hand, if a person calls people in many different area codes and each of these codes has a different frequency, then the volume of traffic is unevenly spread amongst those areas, and that person will have a higher cluster diversity score. In our system, the "area code" is defined as the element's cluster.

Appendix 2: List of elements of student retention and rationale

Name	Description	Rationale
Age	Age on first day of the first academic year of enrolment	Bruinsma and Jansen 2007; Jansen and Bruinsma 2005; Van den Berg and Hofman 2005; Van der Hulst and Jansen 2002; Prins 1997.
Gender		Araque et al. 2009; Georg 2009; Vogt 2008; French et al. 2005; Jansen and Bruinsma 2005; Van den Berg and Hofman 2005; Zhang et al. 2004; Beekhoven et al. 2003 2002; Moller-Wong and Eide 1997; Felder et al. 1994.
SE_math	Secondary Education grade math	Oseguera and Rhee 2009; Bruinsma and Jansen 2007; Jansen and Bruinsma 2005; Beekhoven et al. 2004, 2003, 2002; Zhang et al. 2004; Van der Hulst and Jansen 2002; Prins 1997; Moller-Wong and Eide 1997.
SE_physics	Secondary Education grade physics	Jansen and Bruinsma 2005; Van der Hulst and Jansen 2002; Prins 1997.
Prior_ed	Secondary Education profile or other prior education	Warps et al. 2010; Prins 1997; Moller-Wong and Eide 1997.
Language_Dutch	Self rating on 5 point scale: Mastery of language	Warps et al. 2010; Burtner 2008; Jansen and Bruinsma 2005; Van der Hulst and Jansen 2002.
Language_Eng	Self rating on 5 point scale: Mastery of language	Warps et al. 2010; Burtner 2005; Jansen and Bruinsma 2005; Zhang et al. 2004; Van der Hulst and Jansen 2002; Moller-Wong and Eide 1997; Besterfield-Sacre et al. 1997.
Skill_math	Self rating on 5 point scale: math skills.	Vogt 2008; Burtner 2005; Veenstra 2008; Jansen and Bruinsma, 2005; Prins 1997; Besterfield-Sacre et al. 1997.
Skill_physics	Self rating on 5 point scale: physics skills	Vogt 2008; Burtner 2005.
Skill_comp	Self rating on 5 point scale: computer skills	Warps et al. 2010; Vogt 2008; Burtner 2005.
Traveltime_tot	Commute to campus per week in hours	Van den Bogaard 2011
N_travel_days	N days travel to campus	Van den Bogaard 2011
Ed_parents	Do parents have a degree in Higher Education	Warps et al. 2010; Georg 2009; Araque et al. 2009; Oseguera and Rhee 2009; Bruinsma and Jansen 2007; Jansen and Bruinsma 2005; Van den Berg and Hofman 2005; Beekhoven et al. 2003, 2002; Felder et al. 1998, 1994, 1993.
B_Ment_profile	STEM profile combination of profiles based on Beta-mentality model.	Woodcock et al. 2013; Warps et al. 2010; Burtner 2005; Besterfield-Sacre et al. 1997; Felder et al. 1993.

Member_frat	Membership of student fraternity	Van den Bogaard 2011, Berger and Milem 1999; TH Delft 1958.
Membership total	Membership of any fraternity, sports or cultural association	Van den Bogaard 2011; Warps et al. 2010; Berger and Milem 1999; Prins 1997, TH Delft 1958.
Imp_N_Total	Number of physical or learning impairments out of 14 predefined impairments and 2 options to fill out another impairments.	Warps et al. 2010, Beekhoven et al. 2004.
Housing_sit	Housing situation	Warps et al. 2010; Oseguera and Rhee 2009; Beekhoven et al. 2004.
Expec_diff	Does difficulty programme match expectations. Rating on 5 point scale.	Warps et al. 2010; Jansen and Bruinsma 2005; Beekhoven et al. 2002; Need, De and Jong 2001.
Expec_interest	Do you find your studies as interesting as you expected? Rating on 5 point scale.	Warps et al. 2010; Beekhoven et al. 2002; Need, De and Jong 2001; Thomas 2000.
Expec_BSA	Do you expect a positive re enrollment advice (half of credits of 1 st year)? Rating on 5 point scale.	Beekhoven et al. 2002; Thomas 2000; Prins 1997; Cabrera et al. 1992.
Important_Delft	Importance of studying /obtaining a degree in Delft. Rating on 5 point scale.	Beekhoven 2002; Warps et al. 2010; Thomas 2000; Cabrera et al. 1992
Important_P	Importance of obtaining P diploma in 1 st year. Rating on 5 point scale.	Warps et al. 2010; Beekhoven et al. 2002; Need, De and Jong 2001; Thomas 2000.
PR_total	Number of PR related activities students have participated in.	Warps et al. 2010, French et al. 2005
All questions on teachers (indicated with Tc), assessment (indicated with Ts) and facilities (indicated with Fc) were rated on a 5 point scale. The questions on curriculum organizations (indicated with Oo) were rated on a 4 point scale.		
Tc_content	Teacher has plenty of content knowledge.	Bruinsma and Jansen 2007; Jansen and Bruinsma 2005; Beekhoven et al. 2002; Prins 1997
Tc_explain	Teachers can explain concepts in different ways.	Warps et al. 2010; Bruinsma and Jansen 2007; Jansen and Bruinsma 2005; Beekhoven et al. 2002; Prins 1997
Tc_hall	Teachers take time to answers questions from students in the lecture hall.	Bruinsma and Jansen 2007; Jansen and Bruinsma 2005; Beekhoven et al. 2002; Need, De, and Jong 2001; Prins 1997
Tc_master	Teachers have truly mastered the subjects they teach.	Bruinsma and Jansen 2007; Beekhoven et al. 2002; Prins 1997
Tc_available	Teachers are available when students have questions.	Warps et al. 2010; Vogt 2008; Bruinsma and Jansen 2007; Jansen and Bruinsma 2005; Beekhoven et al. 2002; Need, De, and Jong 2001; Prins 1997

Tc_empathize	Teachers can empathize with the students.	Warps et al. 2010; Vogt 2008; Bruinsma and Jansen 2007; Beekhoven et al. 2002; Need, De and Jong 2001; Prins 1997
Tc_enthusiasm	Teachers are enthusiastic about their courses.	Warps et al. 2010; Vogt 2008; Bruinsma and Jansen 2007; Beekhoven et al. 2002; Prins 1997
Ts_proj	In projects expectations are clear.	Van den Bogaard 2011; Warps et al. 2010;
Ts_constr	Feedback on project is constructive	Van den Bogaard 2011; Warps et al. 2010.
Ts_consist	Feedback on project is consistent	Van den Bogaard 2011;
Ts_trans	Final feedback on project is transparent.	Van den Bogaard 2011; Warps et al. 2010;
Ts_exp	In exams expectations are clear.	Van den Bogaard 2011; Warps et al. 2010; Need, De and Jong 2001.
Ts_feedback	Feedback on formative tests was constructive.	Van den Bogaard 2011; Warps et al. 2010;
Ts_level	Level of exams was representative of course level.	Van den Bogaard 2011.
Ts_repres	Content of exams was representative of course.	Van den Bogaard 2011.
Ts_time	Enough time to sit the exam.	Van den Bogaard 2011.
Fc_atm	There is a good atmosphere at the faculty.	Van den Bogaard 2011; Warps et al. 2010; Beekhoven et al. 2004, 2002.
Fc_studyF	There are plenty of working spaces to study quietly at the faculty.	Van den Bogaard 2011; Warps et al. 2010.
Fc_studyC	There are plenty of working spaces to study quietly on the campus.	Van den Bogaard 2011; Warps et al. 2010.
Fc_relax	There is plenty of space to relax at the faculty.	Van den Bogaard 2011; Warps et al. 2010.
Fc_stmen	Student mentor was accessible.	Van den Bogaard 2011; Warps et al. 2010; Beekhoven et al. 2002.
Fc_tcmn	Teacher mentor was accessible.	Van den Bogaard 2011; Warps et al. 2010.
Fc_studsup	Study support is accessible.	Van den Bogaard 2011; Warps et al. 2010; Beekhoven et al. 2002.
Oo_spread	Course load was spread unevenly.	Van den Bogaard 2011; Warps et al. 2010, Jansen and Bruinsma 2005; Need, De and Jong 2001.
Oo_material	Materials were difficult to understand.	Van den Bogaard 2011; Warps et al. 2010.
Oo_late	Materials were not available or too late.	Van den Bogaard 2011; Warps et al. 2010, Need, De and Jong 2001.
Oo_book	It was difficult to find out what books/materials we needed to study.	Van den Bogaard 2011; Warps et al. 2010.
Oo_feedback	I received insufficient feedback.	Van den Bogaard 2011; Warps et al. 2010.
Oo_courses	The courses did not appeal to me.	Van den Bogaard 2011; Warps et al. 2010.

Indicators of Student behaviour are included in a large number of studies, for example Warps et al. 2010, Seymour and Hewitt 1997, TH Delft 1958. The items below are based on Zimmerman and Kitsantas (2007) and Schmitz and Wiese (2006).		
Sb_goal	I set goals and stick to them.	
Sb_syst	I don't study systematically.	
Sb_tempo	The pace of the programme is too high for me.	
Sb_deep11	When I study I truly want to understand it.	
Sb_exam	I mainly study for the test.	
Sb_behind	I'm always behind on my work.	
Sb_bursts	I work in bursts.	
Sb_eff	I work out strategies to spend my time efficiently.	
Sb_hard	I fail to work hard enough.	
Sb_enough	I don't do enough for my studies.	
Sb_pause	I interrupt myself often and take breaks.	
Sb_keepup	I keep up with my work.	
Sb_toomuch	I have too much going on.	
Sb_concen	I can concentrate well, even if I find a subject tough.	
Sb_help	If I can't work it out myself, I find help.	
Sb_forget	After exams I forget everything again quickly.	
Sb_mark	I want to pass the test, I don't care for the mark.	
Sb_deep12	When I wrap up a course, I want to feel like I really learned something.	
Sb_check	If I fail a test, I go in to check my mistakes.	
Sb_prep	When I fail an exam, I will prepare in a different way next time.	
N_courses	Number of courses scheduled in one education period	Jansen and Bruinsma 2005; Van den Berg and Hofman 2005; Van der Hulst and Jansen 2002
N_exams	Number of exams scheduled in one education period.	Jansen and Bruinsma 2005; Van den Berg and Hofman 2005; Van der Hulst and Jansen 2002
N_active	Number of scheduled hours for active teaching formats, such as projects and practicals.	Jansen and Bruinsma 2005; Van den Berg and Hofman 2005; Van der Hulst and Jansen 2002
N_lectures	Number of scheduled hours of lectures.	Jansen and Bruinsma 2005; Van den Berg and Hofman 2005; Van der Hulst and Jansen 2002

N_mandatory	Number of scheduled hours where presence is mandatory.	Van den Bogaard 2011
P_EC_N	Number of credits obtained in first year.	