Extension of Liskov Substitution Principle and Application to Curriculum Management

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Abstract: This paper offers an extension of the Liskov substitution principle by means of compatible systems, i.e., right or appropriate or functional systems. The compatible systems are represented by compatible sets. The compatible sets are first defined and the new approach to the mathematical modelling of compatible systems is given. The properties of compatible systems are next presented and applied to the curriculum management in higher education. The theoretical results are exemplified by a case study that discusses the curriculum management of two academic programs of study using the information densities of optional, fundamental and specialized courses. A discussion on the systems compatibility in several fields is included and the importance of our multidisciplinary approach to compatible resources management is highlighted.

Keywords: compatible sets; compatible systems; curriculum management; information density; Liskov substitution principle; mechatronics

1 Introduction

Following the unprecedented development of science and the emergence of interdisciplinary or border branches, specializations in one area can provide explanations and ways to solve the other. Highly contoured borders of some sciences and courses have disappeared. Engineering including mechatronics has multidisciplinary applications in medicine, efficient management forces engineers to have economic knowledge, economists have knowledge of engineering and all students must maximize the outcome of their knowledge.

Researchers and specializations of academic courses must provide each other knowledge and use specific compatible tools in the curriculum management. The multidisciplinary specialized intellectual resources must be used because of the benefits in terms of value of time and need for excellence.

Since the above aspects have not been proved mathematically, this paper provides the definition of compatible sets by the extension of the Liskov substitution principle (LSP) [1]. This is motivated by numerous examples from different fields that relate in similar terms to elements, sets, activities, which not identical, but compatible insofar as each has a density of identical information. With this regard the main purpose of this paper is to offer a modelling approach that characterizes the compatible systems or sets in the same environment and to apply our approach to academic curriculum management.

This paper uses the symbol ω to indicate the compatibility relation. In this context, the notation $x \omega y$ outlines that elements $x \in X$ and $y \in Y$ are compatible. As shown in [2], if A and B are independent systems, the problems of the system A are solved using the system B given that:

- both systems contain compatible elements called mirror elements,
- both systems operate in the same environment.

Under these conditions, two or more systems can be compatible. Therefore, the compatibility is defined in [2] as the capacity of two or more systems or components to carry out all tasks as long as they operate in the same environment.

The new idea of this paper stems from the characterization of systems and of their elements given in [2]: if in the system S_A represented by the set A all elements are considered known and the elements $x_{\omega yi}$ are unknown, and if in the system S_B represented by the set B all elements are considered known including the elements $y_{\omega xi}$, and if the elements $x_{\omega yi}$ are compatible with the elements $y_{\omega xi}$, then, replacing between them the compatible elements or the mirror elements, the system S_A will be considered resolved or functional. This means that the system S_A is compatible with the system S_B, and we use the notation $S_A \omega S_B$.

This paper extends this result by suggesting operations on compatible systems and their characterization by the information density of a system. Programs of study in higher education are targeted.

This paper is organized as follows: the background is presented in the next section. Section 3 is dedicated to the new approach to modelling of compatible systems. The properties of compatible systems are formulated and proved. Section 4 validates the theoretical approach by a case study focused on the curriculum management of two academic programs of study. The conclusions are pointed out in the final section.

2 Background

Many theories on the connection between the performance and the human resource management have been proposed recently [3-5]. Due to the market changes, the schools and universities have become increasingly managerially in their approach [6].

This paper offers a theory and some technical points of view on how to generally keep the freedom, the autonomy and the identity by offering, at the same time, the possibility to co-operate if the fields of activity are compatible. We focus on the academic field as a representative example due to its importance [7-10].

The concept of compatible is often used in the theory of systems of equations. Thus, a system of equations is called compatible if the system has at least one solution. The probability theory states that two events A and B are compatible if they take place in the same sample, namely, if they have at least one common favourable case.

The LSP is very close to compatibility. This principle states that [1] if A is a subtype of B, then objects of type B may be replaced with objects of type A (i.e., objects of type A may be substituted by objects of type B) without altering any of the desirable properties of the environment where A and B exist. As shown in [1], if these conditions are fulfilled in a computer program, the desirable properties of that program (correctness, tasks performed, etc.) are not altered. In addition, the subtypes should fulfil certain constraints.

This paper proposes the need to treat the compatible systems by an extension of the LSP on the basis of observing the common elements of this principle in various fields. The concept of compatible will be used in the sense of right or appropriate or functional. For example, software compatibility is in question when referring to compatible online games; this concerns the ability of a software program to run in a particular operating system. The new contribution of this paper is important because the literature analysis conducted as follows points out the absence of models to characterize all compatible systems. Moreover, our modelling approach can be uses in human resources management and, more general, in compatible resources management. These aspects are advantageous with respect to the state-of-the-art because we bridge the compatibility gap between systems in different fields by a systematic modelling approach.

The electromagnetic compatibility is discussed in [11, 12] from the general point of view of the ability of an equipment or system to perform without introducing intolerable disturbances to anything in the same environment; the applications can be related to sensitivity or robustness issues. The compatibility in divergent market systems is studied in [13]; it is proved that the compatibility can be slightly modified if the market is served by fully integrated system suppliers. The compatibility and substitutability of roles in multi-agent systems are analysed in

[14]; a formal specification of role-based interactions components along with their composition is suggested. The compatibility in mechanics refers to the conditions under which a displacement field can be guaranteed, and compatibility conditions are considered in [15] as particular cases of integrability conditions in the framework of the linear elasticity theory. The compatibility in medicine is related to medical and/or technical subsystems that should operate together in order to achieve several well defined goals with emphasis on robotics [16-21]. The use of innovation related to the compatibility in higher education is analysed in [22] with focus on team-based learning. Several problems related to the Bologna process are treated in [23, 24]. The need for experiments in control engineering and mechatronics education is pointed out in [8, 25-30].

In the context of the previous section, we consider that an element $x \in X$ is compatible with an element $y \in Y$ if, by replacing x with y, the new system $S_{A'}$ represented by the set $A' = \left(A \setminus \{x\}\right) \cup \{y\}$ is functional.

We consider two systems operating in the same environment, namely S_A represented by the set A and S_B represented by the set B, both of them having a finite number of elements that characterize each of the systems:

$$A = I \cup X_{\omega y} \cup X\,, \tag{1}$$

$$B = I \cup Y_{\omega x} \cup Y\,, \tag{2}$$

where the subsets in (1) and (2) are expressed as

$$\begin{gathered} I = \{id_j \mid j = 1...m\}, X_{\omega y} = \{x_{\omega yk} \mid k = 1...p\}, X = \{x_i \mid i = 1...n\}, \\ Y_{\omega y} = \{y_{\omega xk} \mid k = 1...p\}, Y = \{y_j \mid j = 1...r\}, \end{gathered} \tag{3}$$

and the subsets $X_{\omega y}$ and $Y_{\omega y}$ fulfil the following properties [2]:

- They have the same number p of elements.
- The elements $x_{\omega yk}$ and $y_{\omega xk}$ are compatible elements or mirror elements, these elements can take the place of, or substitute each other without being identical.
- The identical element $id_j \in I$ is not compatible, and a compatible element is not necessarily an identical element.
- The sets A and B are named compatible if the subset $C_{ms} = C_{ms}(A, B)$ consisting of identical elements, together with the compatible elements (mirror elements), delimits a set of minimum or sufficient characteristics.
- If $x_i \in X \cap Y$, then x_i is called an identical element.

An example to illustrate the structure of the two sets A and B is presented in Figure 1.

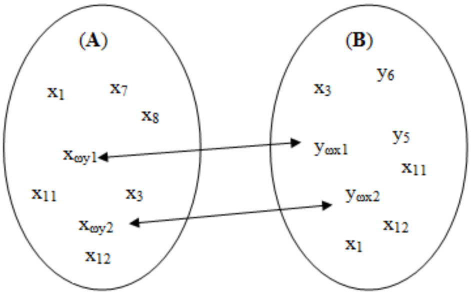

Figure 1
Structure of sets A and B

3 Mathematical Modelling Approach

The compatible sets A and B are represented by the subset C_{ms} of minimum or sufficient characteristics for which a system S characterised by C_{ms} is functional. The structure of the subset C_{ms} is presented in Figures 2 and 3.

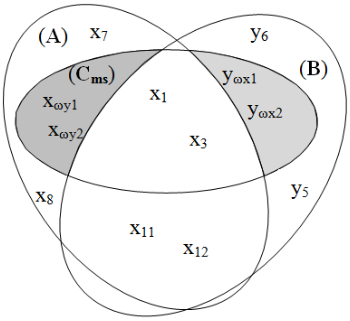

Figure 2
General structure of subset C_{ms}

The identical element $x_i \in X \cap Y$ is not necessary to the two systems S_A and S_B to be functional. This is highlighted in Figure 2 by the two elements x_{11} and x_{12}.

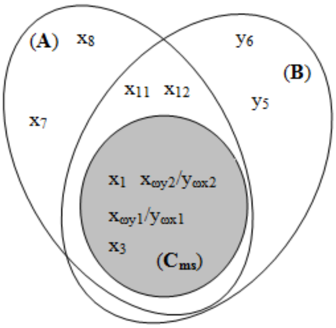

Figure 3
Subset C_{ms} represented as a subset of minimum or sufficient characteristics

The subset $C_{ms} = C_{ms}(A, B)$ is defined as follows [2]: if

$$X_{A/B} \subseteq X_{\omega y} \cup Y_{\omega x},\ |X_{A/B}| = |X_{\omega y}| = |Y_{\omega x}|, \tag{4}$$

then

$$C_{ms} = C_{ms}(A, B) = I \cup X_{A/B} \cup (X \cap Y), \tag{5}$$

where $|X|$ is the cardinal of the set X.

The additional characteristics C_{ad}:

$$C_{ad} = (A \cup B) \setminus C_{ms} \tag{6}$$

do not define, from the point of view of compatibility, the sets A and B. This is pointed out by the elements x_7, x_8, y_5 and y_6 in Figure 3.

As shown in [2], there is a bijective function f that fulfils

$$\begin{aligned} &f : B \setminus Y \to A \setminus X, \\ &f(id_j) = id_j \text{ for } id_j \in I,\ \ f(y_{\omega x}) = x_{\omega y},\ y_{\omega x} \in Y_{\omega x}. \end{aligned} \tag{7}$$

This function and the inclusion of the identical elements lead to a different representation of Figure 2, shown in Figure 4. Figure 4 highlights both the identical elements id_j and the unnecessary elements x_{11} and x_{12}.

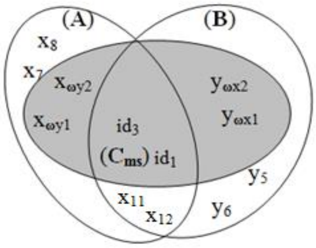

Figure 4

Structure of subset C_{ms} with identical and unnecessary elements included

The properties of the compatibility relation will be presented as follows. These properties are next applied in Section 4.

Proposition 1 (reflexivity). Let the system S_A be represented by the set A. Then $S_A \,\omega\, S_A$.

Proof. Since the system S_A is represented by the set A, there is a minimum set of characteristics $C_{ms}(A, A)$ for which the systems S_A and S_A are compatible, i.e.

$$C_{ms}(A,B) = I \cup X_{A/A} \cup X = A. \tag{8}$$

Proposition 2 (symmetry). If the relation $S_A \,\omega\, S_B$ holds, then $S_B \,\omega\, S_A$.

Proof. Since the system S_A is compatible with the system S_B, there is a minimum set of characteristics $C_{ms}(A, B)$ for which the systems S_A and S_B are compatible, i.e.

$$C_{ms}(A,B) = I \cup X_{A/B} \cup (X \cap Y) = I \cup X_{B/A} \cup (Y \cap X) = C_{ms}(B,A). \tag{9}$$

Equation (9) indicated that the system S_B is compatible with the system S_A.

Proposition 3 (transitivity). If the relations $S_A \,\omega\, S_B$ and $S_B \,\omega\, S_C$ hold, then $S_A \,\omega\, S_C$.

Proof. Since the system S_A is compatible with the system S_B, there is a minimum set of characteristics $C_{ms}(A, B)$ for which the systems S_A and S_B are compatible, and equation (5) is applied. Since the system S_B is compatible with the system S_C, there is a minimum set of characteristics $C_{ms}(B, C)$ for which the systems S_B and S_C are compatible, and the following equation similar to (5) is applied:

$$C_{ms}(B,C) = I \cup X_{B/C} \cup (Y \cap Z), \tag{10}$$

where the set Z is defined similarly to the sets X and Y in (1), (2) and (3), but this set corresponds to S_C.

Using the definitions of the systems S_A, S_B and S_C represented by the sets A, B and C, respectively, it follows that there exist a minimum set of characteristics $C_{ms}(A,C)$

$$C_{ms}(A,C) = I \cup X_{A/C} \cup (X \cap Z), \tag{11}$$

so the systems S_A and S_C are compatible.

These three propositions result in the conclusion that the compatibility relation ω between two systems is an equivalence relation on the set of systems. An equivalence class is given as

$$\hat{S}_A = \{S_B \mid S_A \, \omega \, S_B\}. \tag{12}$$

The antisymmetry property cannot be proved on the compatible sets because these sets also include compatible components that are not identical.

4 Case Study Concerning Curriculum Management

Two programs of study S_{P_1} and S_{P_2}, represented by the sets P_1 and P_2, are considered in order to exemplify relatively easily the two systems compatibility:

$$\begin{gathered} P_1 = C_o \cup C_f \cup C_s, \\ C_o = \{oc_i \mid i = 1...n\},\ C_f = \{fc_j \mid j = 1...m\},\ C_s = \{sc_k \mid k = 1...p\}, \end{gathered} \tag{12}$$

$$\begin{gathered} P_2 = C_o^* \cup C_f \cup C_s^*, \\ C_o^* = \{oc_i^* \mid i = 1...n^*\},\ C_f = \{fc_j \mid j = 1...m\},\ C_s^* = \{sc_k^* \mid k = 1...p\}, \end{gathered} \tag{13}$$

where oc_i and oc_i^* are the optional courses, fc_j are the fundamental / imposed courses, sc_k and sc_k^* are the compatible specialized courses, C_o and C_o^* are the sets of optional courses, C_f is the set of fundamental courses, C_s and C_s^* are the sets of compatible specialized courses.

Equations (12) and (13) point out that

$$|C_s| = |C_s^*|, \tag{14}$$

namely the two sets of compatible specialized courses have the same number of compatible elements.

We will evaluate the properties of the sets C_o, C_f, C_s, C_o^* and C_s^* in a case study related to two academic programs of study, an engineering program S_{P_1} and an economic program S_{P_2}.

C_o and C_o^* may also be empty sets, and they are insignificant sets not as a number but in the subject matter. Examples of insignificant sets or courses for these two programs of study are Sports and Languages.

$C_f \neq \varnothing$ for these programs of study. Examples of courses from this set are Statistics, Mathematics and Control Engineering.

Each element $fc_j \in C_f$ is characterized by the information density $\rho(fc_j)$, with

$$\rho(fc_j) > \rho_{acc}(fc),\ j = 1...m, \tag{15}$$

where $\rho_{acc}(fc)$ is the accepted threshold of density of fundamental courses. The parameter $\rho_{acc}(fc)$ is fixed.

$C_s \neq \varnothing$ and $C_s^* \neq \varnothing$ for these programs of study. Examples of courses from these sets are Management and Investments.

Each element $sc_k \in C_s$ is characterized by the information density $\rho(sc_k)$, with

$$\rho(sc_k) > \rho_{acc}(sc),\ k = 1...p, \tag{16}$$

where $\rho_{acc}(sc)$ is the accepted threshold of density of specialized courses. The parameter $\rho_{acc}(sc)$ is also fixed.

The densities can be quantified and measured. They are related as follows to the intersection and union of compatible sets with emphasis on the curriculum management.

If S_{P_1}, S_{P_2}, ..., S_{P_q} are compatible programs of study, the intersection of sets containing the compatible (mirror) elements is defined as the set $P_1 \cap_\omega P_2$

$$P_1 \cap_\omega P_2 = P_1 \cap P_2 \cup X_{P_1/P_2}, \tag{17}$$

where

$$X_{P_1/P_2} = \{sc_k \vee sc_k^* \mid k = 1...p\}. \tag{18}$$

The set X_{P_1/P_2} allows for the definition of a matrix of programs of study.

The academic curriculum results in three types of professions from the point of view of compatible resources management:

- Profession, which is given by the university diploma or licence or certificate.
- Border profession, built by supplementing a core profession with specific sufficient partial knowledge belonging to other professions. This type represents an effect of relevant rules or of special laws, e.g., mediator, assessor of property, industrial property attorney. The border profession is not a quality of the main profession.
- Specialization, which completes the curricular area by increasing the quality and / or the scope of profession. The specialization is not a profession itself. A specialization course without faculty cannot give equal rights with those conferred by the university diploma.

Therefore, we define the notion of admissible information density ρ_{adm} as the value under which complementary or mirror elements are not allowed. The admissible information density ρ_{adm} in higher education can be, for example, the sum of credits of the courses C_f, C_s and C_s^*. In fact, the compatible elements are some sets (i.e., they represent the information within the programs S_{P_1} and S_{P_2} in this case study) of a certain information density.

We define the representativity value associated to the program S_{P_1} as $V(P_1)$

$$V(P_1) = \sum_{j=1}^{m} fc_j + \sum_{k=1}^{p} sc_k \ , \tag{19}$$

and the representativity value associated to the program S_{P_2} as $V(P_2)$

$$V(P_2) = \sum_{j=1}^{m} fc_j + \sum_{k=1}^{p} sc_k^* \ . \tag{20}$$

Thus, for the programs S_{P_1} and S_{P_2} to be compatible, their representativity values $V(P_1)$ and $V(P_2)$ must fulfil the conditions

$$\begin{aligned} &V(P_1) > \rho_{adm}, \\ &V(P_2) > \rho_{adm}. \end{aligned} \tag{21}$$

If S_{P_1}, S_{P_2}, ..., S_{P_q} are compatible programs of study, the union of sets containing the compatible (mirror) elements is defined as the set $P_1 \cup_{\omega} P_2$

$$P_1 \cup_\omega P_2 = C_o \cup C_o^* \cup C_f \cup X_{P_1/P_2}, \tag{22}$$

The set $P_1 \cup_\omega P_2$ in this case study is the mathematical expression of the curriculum. The set $P_1 \cup_\omega P_2$ also represents all programs generated by P_1 and P_2 to be compatible:

$$S_{P_1} \cup_\omega S_{P_2} = \hat{S}_{P_1} = \hat{S}_{P_2}\,. \tag{23}$$

The number of programs of study generated by P_1 and P_2 is $N(P_1, P_2)$

$$N(P_1, P_2) = 2^{n+n^*}\binom{2p}{p}. \tag{24}$$

As a result, the programs generated by S_{P_1} and S_{P_2} offer an image on the compatible elements through the courses Management and Investments. If these courses respect in both programs an at least above ρ_{adm}, then these will contain complementary or mirror courses or items. Therefore, the exchange of experts or teachers will be not only acceptable but also useful to those national or international educational systems where the optimisation focusing on the cost minimisation is required. An objective function that can be used with this regard is

$$J = |C_o \cup C_f|\,. \tag{25}$$

The optimisation problem must be correctly defined and associated with the correct definition of the variables of the objective function J and of the constraints. One such constraint concerns the set C_o that belongs to curricular areas and is given by laws.

The profit optimisation can be targeted as well. But this objective involves a different objective function.

Unfortunately, in education, the profit optimisation does not offer a competitive level of preparation, but just a sufficient one. Therefore national bodies involved in decision making in the educational systems should pay special attention to this subject.

The cost optimisation and the profit optimisation lead to minimum and maximum curricular areas. These areas are used in the assessment of the private higher education. However, the cost optimisation and the profit optimisation can be combined in terms of multi-objective optimisation problems. All these optimisation problems must be solved by appropriate algorithms [31-37].

Fuzzy logic can also be involved in our modelling approach [38-44]. The information density values $\rho(fc_j)$ and $\rho(sc_k)$ can be normalised as follows:

$$\begin{aligned}&\rho_n(fc_j)=\rho(fc_j)/\sum_{\iota=1}^{m}\rho(fc_\iota),\ j=1...m,\\&\rho_n(sc_k)=\rho(sc_k)/\sum_{\tau=1}^{p}\rho(sc_\tau),\ k=1...p,\end{aligned}\tag{26}$$

where the normalised information densities $\rho_n(fc_j)$ and $\rho_n(sc_k)$ fulfil the conditions

$$\begin{aligned}&0\le\rho_n(fc_j)\le 1,\ j=1...m,\\&0\le\rho_n(sc_k)\le 1,\ k=1...p.\end{aligned}\tag{27}$$

We define two fuzzy sets. The first fuzzy set is (C_f,μ_1), with the membership function μ_1

$$\begin{aligned}&\mu_1:C_f\to[0,1],\\&\mu_1(fc_j)=\begin{cases}\rho_n(fc_j), & \text{if } \rho_n(fc_j)>\rho_{acc}(fc),\\ 0, & \text{otherwise},\end{cases}\ j=1...m.\end{aligned}\tag{28}$$

The second fuzzy set is (C_s,μ_2), where the membership function μ_2 is

$$\begin{aligned}&\mu_2:C_s\to[0,1],\\&\mu_2(sc_k)=\begin{cases}\rho_n(sc_k), & \text{if } \rho_n(sc_k)>\rho_{acc}(sc),\\ 0, & \text{otherwise},\end{cases}\ k=1...p.\end{aligned}\tag{29}$$

These two fuzzy sets are an alternative to the modelling of academic curricula. They can be embedded in decision making using the well acknowledged operators specific to fuzzy logic.

Conclusions

This paper has proposed an extension of the LSP by means of compatible systems. A mathematical modelling approach that involves information densities has been proposed and applied to the curriculum management of two academic programs of study.

Our mathematical modelling approach is presented by means of specific properties of compatible systems and elements including the definition of fuzzy sets. This aspect will be treated as a future research direction by offering a clear modelling algorithm organised in terms of clear steps that should highlight the presence of control systems and mechatronics applications [45-56] in the courses of the engineering programs of study. The generalization to an arbitrary number of programs of study will be treated.

The future research will be focused on more convincing educational applications and on the analysis and design of compatible control systems. The further extensions of our modelling approach by fuzzy sets will enable the investigation of tools for the analysis and design fuzzy control systems.

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