Schedule and Cost Control in Dwelling Construction Using Control Charts

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Abstract: Methods to monitor the schedule and to control cost in dwelling construction projects are numerous and varied but commonly constitute an obstacle to a fast and agile response by construction managers, whose decisions require information to be comprehensive and summarized. A simple model to monitor these projects is proposed that can easily be implemented within control systems that are already in place. For the first time, process control charts are combined with cost control in dwelling construction in order to prevent overruns in terms of time and/or cost. The model facilitates the production supervision of construction contracts by regularly providing information on the work completed and the incurred cost of the production processes per period, through charting and/or summarizing this information in a manner consistent with statistical control charts. Finally, the manager can easily identify those processes which are off target by consulting control charts.

Keywords: Cost control, dwelling construction, project management, scheduling, statistical process control, work breakdown system.

1. INTRODUCTION

Over the last decade, an abundance of project control methods have been developed and a variety of software packages have become available to support their application, [1-3]. However, project planning and cost control still remain an open issue. Olawele and Sun [4] performed a survey to establish the current common practice of time and cost control in the UK construction industry, and include control methods and software applications in use. They identified the importance of cost and time control; already widely recognized by construction professionals. Their questionnaire survey reveals that 58% of respondents always apply time controls to their project and an overwhelming 84% implement cost control methods. These authors also identify the most popular time-planning and control techniques. The Gantt Bar Chart [5] is the most widely used, closely followed by the Critical Path Method [6]. Another commonly used technique is the Program Evaluation Review Technique, PERT [6]. The use of software support is widespread. Olewale and Sun [4] also detected that the cost control techniques most commonly used in practice, in about 70% of surveys, are project cost-value reconciliation, overall profit and loss, profit and loss at valuation dates, and reconciliation of actual versus forecast labour/plant/material.

Despite the wide variety of control techniques and software available, construction projects are still subject to cost and time overruns. Researchers have been adapting previous techniques to more precise prediction levels through the implementation of stochastic instead of deterministic models. For example, approximations are used in the estimation of the mean and variance of the completion time for a PERT network and the task durations are approximated by employing normal distributions [7]. Other work related to stochastic models focuses on the planning and execution of construction projects, and account for the variability inherent in the duration and cost of the scheduled activities by simultaneously applying range estimation and probabilistic scheduling to historical data [1]. More recently, stochastic analysis by a multiple simulation analysis technique using Monte Carlo simulation has been used to evaluate the impact of non-critical activities for which the deterministic critical path method is insufficient [2].

In industrial processes, certain factors of stochastic behaviour exist whose influence on the process determines variations in the quality of the final product. In order to predict and control this influence, several methods have been developed, such as Statistical Process Control (SPC) [8] which uses statistical indicators to identify common causes of quality variation in manufacturing processes and to reduce the cost. An introductory survey on the subject appears in [9]. Specifically, the result of applying a repetitive process can be represented by a normal distribution whose mean and standard deviation are related to a single quality parameter. Multivariate analyses based on SPC, which are more common in practice, have also been developed over the last two decades [10-12]. In both uni- and multi-variate analysis, statistical measures, such as mean and standard deviation, determine the tolerance levels of the variation with respect to the target, which can be represented in a control chart with regard to time. These charts clearly and promptly show abrupt fluctuations and indicate whether they are due to ei-

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ther a random or an unknown factor which should consequently be taken into account [13]. Thus, managers can adopt corrective decisions in order to reach the final target. More specifically, in the construction industry, SPC has successfully controlled road construction [14] and, combined with the Earned Value Management (EVM) method, project cost and schedule performance have been controlled [15].

In the current paper, a new model to monitor the schedule and to control cost is proposed which adapts, for the first time, SPC control charts to dwelling construction. Dwelling construction usually consists of simple projects for which repetitive work takes place, which makes it possible for the tools already being used in the control of the manufacturing process to be adapted to control the construction process.

Once the schedule is established, by either a deterministic or stochastic approach, it can be controlled and deviations can be corrected. In the present model, schedule and cost control in projects are handled simultaneously. Many models handle resources separately and independently from the time factor, and the cost model is disconnected from the time model, thereby rendering cost and time control difficult and imprecise. Researchers have identified the benefits from integrating cost and schedule control. This is the case of management control by means of the Earned Value Management System (EVMS) which determines the actual costs accumulated and compares them to the earned value [16]. This value is used as a baseline to which the planned schedule (budgeted cost for work scheduled), and the actual cost (actual cost of work performed), are compared in order to measure the schedule performance and cost performance, respectively. The results of performance variances and indices are used for further analysis, which include identifying latent risks, and re-scheduling the remaining work [3].

Following the EVMS approach, the main objectives include the development of a simple tool that allows project managers rapid and agile responses to out-of-budget and/or out-of-schedule processes on the construction site. Three key characteristics are taken into account: a simple structure, ease in data collection, and ease in following the process.

2. METHODOLOGY

The main divisions of the model are similar to those used in EVMS: data input, work scheduling, data transformation into reference values, and comparison between the work actually carried out and planned work completion.

The steps are the following:

- Enter the data of the initial schedule.
- Plan work in terms of cost, using the project schedule.
- Plan work quantities.
- Distribute expected costs and quantities over time periods.
- Enter actual values of work performed and cost produced.
- Compare actual data values against planned data values.
- Calculate cost deviations, and quantity deviations.
- Generate reports for each time period.
- Edit, revise or modify the schedule according to new forecasts.
- Once the schedule is corrected, recalculate the new planned work.

The first step, *Enter the data of the initial schedule*, refers to the original project budget and its planning, (see Fig. **1**). The classification of the costs is obtained from this budget which is organized by means of a work breakdown structure (WBS). The schedule is obtained from the first plan of the project, which allows the work to be distributed into steps for each time period: *Plan cost* and *Plan work quantities* in (Fig. **1**) constitute the "Schedule". This distribution is then used to calculate the accumulative cost and quantities for each period in the step *Distribute expected cost and quantities*, and is represented in (Fig. **1**) as the "Images".

Another set of data is obtained by means of surveys at the construction site, and contains information on the quantities of work performed and costs incurred. This data is compared with the planned values, by subtracting the planned values from the actual values, thereby indicating that an overrun is taking place if a positive value is obtained. The differences during each period are transformed into indicators in the "Evaluation" step in (Fig. **1**), and are represented in a control chart. Finally, a report is written. The schedule is readjusted accordingly and a new work distribution is generated for future comparisons. In the following sections, we define and study each step of (Fig. **1**) in more detail.

2.1. The Data

As established in the previous section, the data needed is the original project budget and planning. The costs are obtained from this budget and the schedule from the initial project time chart. One major aspect in process control is data measurement and accuracy. The method, structure, data, and accuracy of detailed measurement may vary depending on the specific characteristics of a project. This situation can lead to misinterpretation of the project status, especially under a multi-project management environment. In order to overcome this issue, Jung and Kang [3] propose a standard progress measurement package which addresses issues for the standardization of the work breakdown structure (WBS). These authors have identified the measurement of the level of progress as a critical factor in terms of the workload required to maintain both the control system and the accuracy. In order to address this issue, the level of detail for progress measurement should be carefully selected as a trade-off between the workload and accuracy, by incorporating strategy, objectives, and management policy of construction projects.

All WBSs have the same goals and similar methodologies. The basic concept in all of these systems is to divide a complex problem into simpler parts that can then be aggregated to define the development of a complete construction. Many researchers have been working on the development of construction information classification systems (CICS): Kang *et al.* [17] for civil work; Eldin [18]; and Jung *et al.* [3] who address cost and scheduling simultaneously. There are several international CICS, of which the most frequently used include: Masterformat [19], Uniformat II [20], the Civil Engineering Standard Method of Measurement [21], CI/SfB [22], Uniclass [23], and Omniclass [24].

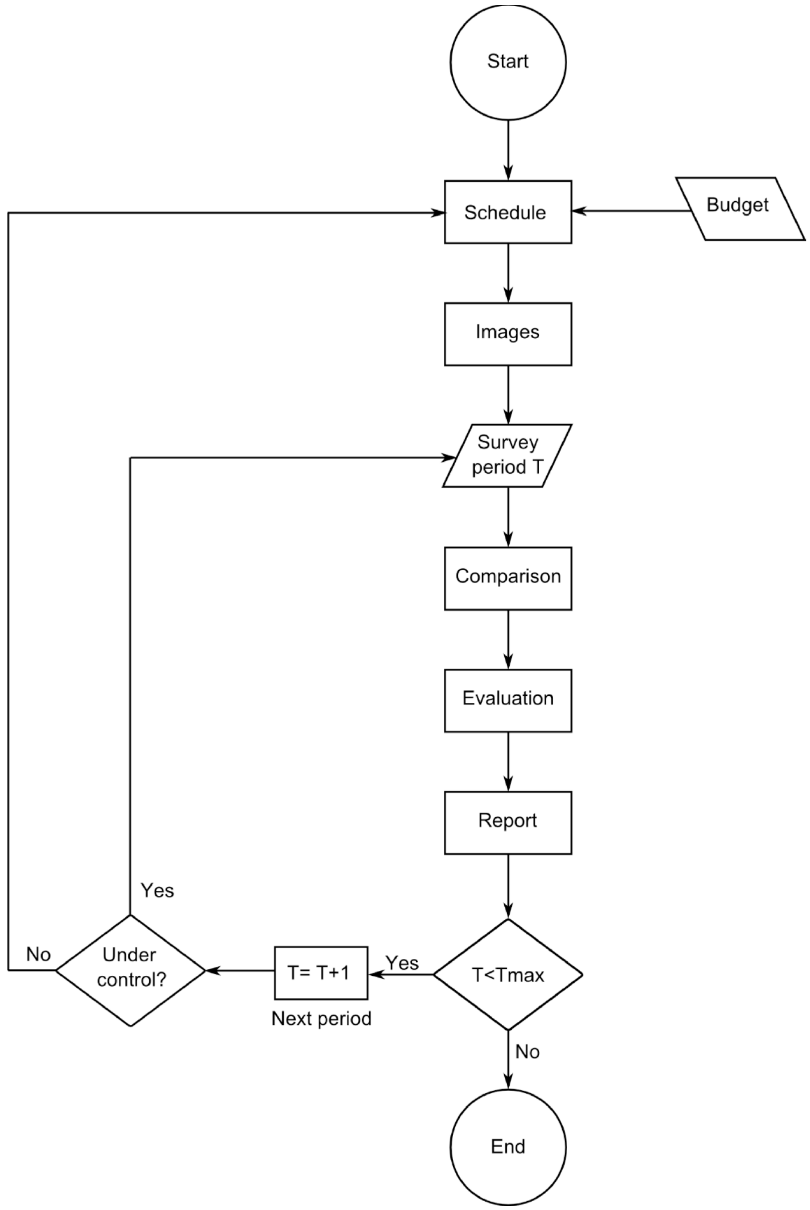

Fig. (1). Steps of the control process.

In particular, the present model uses the Andalusia Construction Information Classification System (ACICS) [25]. Its most extended usage is for estimating cost in dwelling construction and it is mandatory in all public developments in Andalusia, Spain. This system divides work units into a hierarchical organization. The highest level is the construction site, L1 in Table **1**. The next divisions are called chapters, L2 in Table **1**, and each represents a construction process: Demolition, Earthwork, Foundations, Water disposal, Structures, Partitions, Roof, Installations, Insulations, Finishes, Carpentry, Glass and Polyester, Coating, Decoration, Urbanization, Safety, and Waste Management.

The subsequent divisions are the sub-chapters. For example, the chapter called "Installations" is divided into the following sub-chapters: Air conditioning, Electricity, Water, Communications, Gas, Electro-mechanic appliances, Fire protection, and Illumination [26].

Since time and cost are closely related, it can be assumed that a close relationship exists between the cost estimate and schedule. However, it is not easy to numerically evaluate the extent to which these parameters affect each other, due to differences in their breakdown structures [27]. Even though ACICS is developed for the generation of construction budgets, it can also be used for the definition of the schedule. In order to double-check the work development, a second classification system is proposed to control quantities instead of cost. The classification, *complex groups*, is employed to control construction and demolition waste successfully [28, 29]. The complex groups are at the same level as sub-chapters in the ACICS hierarchy. The existence of complex groups allows the combination of similar work units within a chapter, which would not be possible if ACICS sub-chapters were used. For example, earthwork excavations, such as the foundation (02AVV00002), trenches (02ZMM00002), and pits (02PMM00002), have different unitary costs and belong to separate sub-chapter classifications in ACICS: 02A, 02Z, and O2P, respectively, but can still be grouped together into a "complex group", 02EX, since the main activity is common to all of these work units and they can take place during the same period of time, thereby rendering it possible for them to be controlled simultaneously.

Table 1. Internal classification structure.

Class Level	Definitions
L1. Construction site	All the constructive elements that make up a construction site.
L2. Chapter	Element sets with a common characteristic. *e.g.: 05. Structures.*
L3. Sub-chapter	Chapter division into smaller sets with a common characteristic. *e.g.: 05H. Concrete.*
L4. Section	Sub-Chapter division into smaller sets with a common characteristic. *e.g.: 05HH. Reinforced concrete.*
L5. Group	Section division into smaller sets with a common characteristic. *e.g.: 05HHJ. Reinforced concrete beam.*
L6. Work unit	Group division into unitary elements. *e.g.: 05HHJ00001 m3 Concrete HA-25 in....*

The budget is introduced into two different scenarios, work quantities and cost, which is possible since the budget is the result of the addition of all work units that constitute the project, multiplied by their corresponding unitary price. For the first scenario, the sub-chapter cost is defined as,

$$C_s^T = \sum_{i=1}^{l} Q_i P_i \tag{1}$$

where C_s^T is the total cost of sub-chapter "s", and Q_i and P_i are the quantity and price of the work unit "i", which is part of the level "l" total in sub-chapter "s".

The second scenario is for the complex quantities, which are formed of similar work units within the same chapter of the ACICS,

$$Q_g^T = \sum_{i=1}^{m} Q_i \tag{2}$$

where Q_g^T is the total quantity of complex group "g", and "m" is the total number of divisions that are part of the complex group, which implies that all work units in a complex group have the same units of measurement, (cubic metres of concrete, tons of steel, etc).

In order to be able to add and compare widely varying quantities, a coefficient is defined which transforms all quantities into a similar magnitude, D_g,

$$D_g = \frac{P_g}{P_{\max}} \tag{3}$$

where P_g is the average unitary price of the complex group "g" which is measured in monetary units, divided by the corresponding measurement unit, and where P_{max} is the unitary price of the most expensive work unit in the project, divided by the corresponding measurement unit. For dwelling construction, the most expensive unitary price, P_{max}, is normally the average price of all bathroom appliances. This approximation establishes the quantity importance in terms of its proportional unitary price with respect to the most expensive item in the project. The measurement units of D_g are therefore

$$D_g = \left(\frac{u_{\max}}{u_g}\right) \tag{4}$$

where u_{max} is the unit of the most expensive item, and u_g is the group "g" measurement unit. Finally, all complex groups lie within the same complex measurement unit,

$$Q_g \times D_g = u_g \times \left(\frac{u_{\max}}{u_g}\right) = u_{max} \tag{5}$$

Several ASICS work units, which require similar materials, labour, and machinery, are grouped together and their cost is defined as an average. This average cost is subsequently divided by the most expensive work unit in the project, thereby obtaining D_g. For example, in a project where bathtubs are the most expensive work unit at 200 Euro/unit, then 30 m^3 of refilling soil (at 5 Euro/m^3) is transformed into 0.01*30 = 3 units. On the other hand, 30 m^3 of reinforced concrete trenches (at 200 Euro/m^3) is transformed into 30 units. Finally, the D_g factor is able to establish that 30 m^3 of concrete is more important than 30 m^3 of refilling soil due to its unit costs. The advantage of the alternative approach is that different cost estimation is obtained of the cost of the work performed on the construction site, rather than just the cost that is certified and ready for payment. The new quantity approach is independent of market conditions and cost fluctuations since the unitary costs are transformed into a proportion of the original market price, at the beginning of the project, with respect to the most expensive unitary price: the D_g factor. The quantity approach is easily implemented due to the hierarchical nature of the ASICS structure: the families of similar work belong to the same chapter and sometimes to the same sub-chapter. This is the case of reinforced concrete slab (03HAL10002) and reinforced concrete wall (03HAW10007), which belong to sub-chapter 03H and to "complex quantity" 03HA.

2.2. The Schedule

Once the project budget of cost and quantities has been separately input following the ACICS hierarchy, the next step is to define the schedule, also in terms of ACICS. The schedule, which is additional data, is input in two scenarios, one for the cost and another for its corresponding quantities, in terms of ACICS and the complex quantity classification system, respectively. The work quantities and cost are then distributed over the duration of the construction, thereby creating reference scenarios for the actual labour/plant/material versus those planned.

The work units are distributed in time periods, T_k, where the time distribution can be either in terms of man-power hours, days, weeks, machine hours or of any other characteristic that is proportional to the time necessary to perform the work [27], or in terms of program measurement packages [3]. The work amount in period "k" is called weight, W_{sk} and W_{gk}, where "s" or "g" is the sub-chapter or group of which the weight is a component, respectively.

The entire project is planned at the beginning of the controlling process and the planning is revised when the actual work carried out deviates from the work planned.

2.3. The Images

Once the project budget and schedule have been input, then the next step is to create the reference image scenario. In this section the term *image* refers to the representation of the scheduled costs and complex quantities in time. There is an image, planned cost per time period, for each sub-chapter which becomes the reference value. Another image is generated for the complex quantities per period [27]. Thus, if "n" is the total number of periods of the project, then the cost reference images are defined by:

$$C_{sk}^{P} = C_{s}^{T} \frac{W_{sk}}{\sum_{k=1}^{n} W_{sk}} \tag{6}$$

where the planned cost C_{sk}^{P} of sub-chapter "s" in period "k" is obtained as the product of the total cost C_{s}^{T} of sub-chapter "s" obtained from the budget multiplied by the relative proportion of the work to be carried out during such period and sub-chapter, divided by the sum of all the proportions.

In a similar way, the second scenario is defined for the quantities, whereby the reference images are obtained from,

$$Q_{gk}^{P} = Q_{g}^{T} \frac{W_{gk}}{\sum_{k=1}^{n} W_{gk}} \tag{7}$$

where Q_{gk}^{P} is the planned quantity of complex group "g" in period "k", Q_{g}^{T} is the total amount of the complex group "g" obtained from the original budget, and W_{gk} is the proportion of the work of complex group "g" to be carried out in period "k", and "n" is the total number of periods.

2.4. Survey

Once the quantity and cost scenarios are established, then the actual work carried out is noted in a survey during each construction period, which can be defined in terms of days, weeks, or months, depending on the level of time control. The cost survey consists of information about the completed work on the construction site for which the subcontractors are to be paid. The survey is organized in the WBS budget, which is familiar to the construction managers; this aspect facilitates its implementation. The information is normally checked on the construction site in order to control cost as established in the Spanish law on Public Sector Contracts [30].

2.5. The Comparison

Once the survey data is input, the differences between the images for planned quantities and cost and their actual values are determined. Positive differences show overruns and negative differences show work carried out under budget, and constitute the first control level for the construction site manager.

In the succeeding control level, deviation indicators are defined,

$$V_{sk} = \frac{C_{sk}^{R} - C_{sk}^{P}}{\sum_{s=1}^{p}\sum_{k=1}^{n} C_{sk}^{R}} \times 100 \tag{8}$$

$$V_{gk} = \frac{\left(Q_{gk}^{R} - Q_{gk}^{P}\right) \times D_{g}}{\sum_{g=1}^{q}\sum_{k=1}^{n} Q_{gk}^{P} \times D_{g}} \times 100 \tag{9}$$

where V_{sk} is the cost deviation indicator of sub-chapter "s" during period "k" for "p" total sub-chapters and "n" total periods. The indicator is the percentage of cost deviation with respect to the total project budget, and C_{sk}^{R} and C_{sk}^{P} are the actual and the planned costs, respectively.

In the second scenario, V_{gk} is the quantity deviation indicator, Q_{gk}^{R} and Q_{gk}^{P} are the actual and the planned quantities, respectively, of group "g" during period "k" for "q" total groups and "n" total periods. The indicator V_{gk} is the quantity deviation as a percentage with respect to the total project budget.

The total number of groups, g, and the total number of sub-chapters, p, that are part of a chapter, are not fixed since not all dwelling projects are made up of the same number of sub-chapters or groups.

The indicators V_{sk} and V_{gk} are positive values when the process is more expensive than planned or ahead of schedule, respectively, and negative otherwise. Only one indicator is reported per chapter, and is determined as an average value of all the sub-chapter indicators. This assumption allows a simple calculation of the total chapter indicator. For chapter "c" during period "k", the deviation indicators are defined as:

$$V_{ck}^{C} = \frac{\sum_{s=1}^{p} V_{sk}}{p} \tag{10}$$

$$V_{ck}^{Q} = \frac{\sum_{g=1}^{q} V_{gk}}{q} \tag{11}$$

for cost and quantity respectively, where "p" is the total number of sub-chapters and "q" is the total number of complex groups that are part of chapter "c", during period "k". The project deviations, during period "k", are calculated as:

$$V_{Pk}^{C} = \frac{\sum_{c=1}^{r} V_{ck}^{C} \sum_{s=1}^{p} C_{sk}^{P}}{\sum_{c=1}^{r}\sum_{s=1}^{p} C_{sk}^{P}} \tag{12}$$

$$V_{Pk}^{Q}=\frac{\sum_{c=1}^{r}V_{ck}^{Q}\sum_{g=1}^{q}Q_{gk}^{p}D_{g}}{\sum_{c=1}^{r}\sum_{g=1}^{q}Q_{gk}^{p}D_{g}} \tag{13}$$

where "r" is the total number of chapters that make up the project.

2.6. Evaluation and Report

The results need to be reliable, facilitate a rapid knowledge of the situation, and allow an in-depth analysis of the causes. To this end, two analyses are carried out when the survey is compared against the reference image. First a simple report is made and then a control chart is generated.

The control charts are the representation of the indicators of each chapter for each time period, equations (10) and (11), divided by the corresponding standard deviation for the same period. The standard deviation is determined for the population made up by the individual indicators of the sub-chapters. There is a standard deviation determined per time period. First, the mean of the indicators of the complex quantities and sub-chapter costs are calculated, respectively,

$$\bar{V}_{k}^{C}=\frac{\sum_{s=1}^{r}V_{sk}}{r}\ ;\ \bar{V}_{k}^{Q}=\frac{\sum_{g=1}^{r}V_{gk}}{r} \tag{14}$$

where "r" is the total number of sub-chapters or total of complex quantities during period "k".

The standard deviation during the period "k" is then calculated,

$$S_{k}^{Q}=\sqrt{\frac{\sum_{g=1}^{r}\left(V_{sk}-\bar{V}_{k}^{Q}\right)^{2}}{r-1}}\ ;\ S_{k}^{C}=\sqrt{\frac{\sum_{s=1}^{r}\left(V_{sk}-\bar{V}_{k}^{C}\right)^{2}}{r-1}} \tag{15}$$

The control chart centre is set at 0, which indicates that there is no difference between planned and actual values. The upper and lower control limits are established at $\pm 1.5S_{k}^{C}, \pm 1.5S_{k}^{Q}$, for cost and quantity control, respectively. The zone inside these control limits represents approximately 86% of the population in a normal distribution. In SPC, three periods that show an increasing trend towards the upper limit or a decreasing trend towards the lower limit, even though they may remain within the control limits, indicate that the processes need to be corrected [8].

3. CASE STUDY

The previously explained model is used to control the construction of 6,553 m^2 for 48 dwellings in social housing in Cadiz, Spain. The buildings are of six storeys each, with an underground parking area, and a ground level plus another 4 storeys. Each dwelling has a lounge, kitchen, hallway, 3 bedrooms, and one bathroom. The building foundation is a reinforced concrete pad and has reinforced concrete walls for the underground parking area. The rest of the structure consists of concrete footings and one-directional beams. The façade is made of a double brick wall with an insulated cavity, coated with waterproof mortar on the outside, plaster on the inside, and both sides are painted. The finishes are typical for social housing: terrazzo floor, aluminium-framed windows, and wooden interior doors. The roof is flat and transmittable, except for the stairway case which has a sloped roof with Arabic tiles. For the project duration, there is no material nor manpower scarcity. The construction location has no accessibility problems.

In Tables **2** and **3**, the total amount of each sub-chapter is distributed throughout the various time periods. The "code" column refers to the sub-chapter code and the "description" is its corresponding short definition as defined in ASICS. Since the work schedule can be revised several times during the project development, the work already completed during old schedules is entered in the third column, named "base", and the remaining work to be distributed in the new schedule is entered in column 4, named "work". In this way the manager is kept up to date with the amount of remaining work. The column denoted "total" is the sum of all weights in the sub-chapter,

$$Total_{s}=\sum_{k=1}^{n}W_{sk} \tag{16}$$

Finally, columns "T_1, T_2, ..., T_n" represent the weights corresponding to the work distributed in "n" time periods.

Tables **2** and **3** represent the schedule in terms of cost of the first four months of the project. The sub-chapter costs include manpower, materials, and machinery costs. However, the model allows the control level to be focused on any specific aspect, for example, to control only material cost. This is possible since ASICS defines each type of cost, (manpower, material, and machinery), separately within a unitary price. The decision depends on the critical aspect which needs to be controlled more closely.

In Tables **2** and **3**, the work distribution of chapters 02 and 03 (except for sub-chapter 03H) takes place almost completely within the first 4 months, in time periods T_1 to T_4 in the project, and hence the four periods add up to 100 as shown in column "Total". Work of other sub-chapters is not 100 % completed during those four periods and only a partial planning is represented, which adds up to less than 100. In the case study, W_{sk} represents the percentage of work which takes place during period "k". However, other weighting values can be used, such as concrete cubic metres consumed in the foundation during each period; in fact, during each period, any characteristic that describes the work intensity during the project execution can be used. Finally, the total amount of the characteristic is added up in the "Total" column, and the percentage corresponding to each period is determined and is used to define the reference values or *images* in terms of Euros. Similar tables are generated for the schedule in terms of complex quantity classification in Tables **4** and **5**. The main difference between the two tables is the demolition chapter, which does not exist as a "complex quantity" owing to the difficulties in developing new combinations from the cost classification system.

In Tables **4** and **5**, the first and second columns, "code" and "description", are the code from ASICS and a short description, respectively. The "description" contains the measurement unit of the quantities. Additionally, the new

Table 2. The work schedule in terms of cost for the first three chapters and first four months (I).

Code	Description	Base	Work	Total	T_1	T_2	T_3	T_4
01A	Bricks			0				
01C	Foundations			0				
01E	Enclosures			0				
01L	Installations			0				
01K	Carpentry and safety			0				
01Q	Roof			0				
01R	Finishes			0				
01S	Water disposal			0				
01T	Preparation work		631.06	100	100			
01X	Structure			0				
01W	Others			0				
01	**DEMOLITION**		631.06					
02A	Open excavations		2 027.03	100	100			
02P	Pads		39 547.92	100	57	25	18	
02R	Refilled and compacting		454.24	100	57	25	18	
02T	Transport		74 127.52	100	57	25	18	
02W	Others			100	57	25	18	
02Z	Trenches		105.20	100	57	25	18	
02	**EARTHWORK**		116 261.91					
03A	Reinforced steel			0				
03C	Special foundations			0				
03E	Formwork			0				
03H	Concrete		74 127.52	100			20	35
03W	Others			0				
03	**FOUNDATIONS**		74 127.52					
04C	Hanging pipelines		3 319.37	100				
04E	Underground pipelines		9 995.13	100				
04V	Vertical pipelines		854.54	100				
04W	Others		2 126.23	100				
04	**WATER DISPOSAL**		16 295.26					
05A	Steel			0				
05F	Concrete slab		234 691.39	100				
05H	Reinforced concrete		388.34	100				
05M	Wood			0				
05W	Others		6 520.47	100				
05	**STRUCTURES**		241 600.20					
06A	Arches and vaults			0				

(Table 2) contd….

Code	Description	Base	Work	Total	T_1	T_2	T_3	T_4
06B	Concrete blocks			0				
06C	Stone blocks			0				
06D	Brick partitions		22 949.49	100				
06L	Brick walls		111 698.21	100				
06P	Prefabricated			0				
06W	Others		1 031.33	100				
06	**PARTITIONS**		135 679.03					
07H	Horizontal roof		19 275.85	100				
07I	Sloping roof		21 817.44	100				
07W	Others		3 335.64	100				
07	**ROOFS**		44 428.93					

Table 3. The work schedule in terms of cost for the first three chapters and first four months (II).

Code	Description	Base	Work	Total	T_1	T_2	T_3	T_4
08C	Air conditioning			0				
08E	Electricity		1 970.07	100				
08F	Water		1 351.57	100				
08L	Gas			0				
08M	Electro-mechanic appliances		20 306.64	100				
08P	Fire protection		327.73	100				
08V	Audiovisual		17 388.15	100				
08S	Hygiene			0				
08W	Others			0				
08	**INSTALLATIONS**		41 344.14					
09A	Acoustic			0				
09I	Waterproofing		454.24	100				8
09T	Thermal			0				
09W	Others			0				
09	**INSULATION**		454.24					
10A	Cladding		26 124.89	100				
10C	Continuous		49 651.67	100				
10L	Lightweight			100				
10P	Stairs		5 399.16	100				
10S	Floor		70 081.36	100				
10T	Ceiling			100				
10W	Others		102 894.01	100				

(Table 3) contd….

Code	Description	Base	Work	Total	T_1	T_2	T_3	T_4
10	**FINISHES**		254 151.08					
11A	Steel		598.31	100				
11L	Alloys		3 503.23	100				
11M	Wood		21 817.13	100				
11S	Security and safety		24 770.80	100				
11W	Others			0				
11	**CARPENTRY**		50 689.47					
12L	Glass: large format			0				
12V	Glass: small format			100				
12W	Others			0				
12	**GLASS AND PLASTICER**							
13E	Exterior		3 060.51	100				
13I	Interior		11 603.86	100				
13W	Others			0				
13	**COATING**		14 664.36					
14M	Furniture		163.24	100				
14W	Others			0				
14	**DECORATION**		163.24					
15A	Sewers			0				
15C	Safety signalling			0				
15E	Electricity			0				
15G	Gas			0				
15J	Gardening			0				
15M	Earthmoving			0				
15P	Pavement			0				
15S	Water supply			0				
15T	Telephone			0				
15V	Furniture			0				
15W	Others			0				
15	**URBANIZATION**							

coefficient D_g is defined for the current project in the column with the same name. In the project, each sub-chapter average price is divided by the most expensive item in the project: 03HAZ00030 trenches of reinforced concrete, their cost being 168.66 Euro/m^3. For example, the 02EX group has an average cost of 5.06 Euro/m^3 and its corresponding D_g is 0.03.

Once the schedule is defined, the next step involves the collection and organization of the actual data at the construction site. After the data is collected it is input into Tables **6** and **7**, column "C_R" being the real values paid up to that period. A comparison is then performed between the planned scenario (C_P) and the actual scenario (C_R). The C_P column is determined by means of equations (6) and (7), for example the 03H group during period T_4 is the result of the accumulation of previous periods,

$$C_P = 74\ 127.52*(0.0+0.0+0.35+0.20) = 40\ 770.00 \text{ Euros} \quad (17)$$

Table 4. The work schedule in terms of complex quantities for the first three chapters (I).

Code	Description	Base	Q	Dg	Total	T_1	T_2	T_3	T_4
02EX	m^3 Excavation		4 435	0.03	100	57	25	18	
02RR	m^3 Refill		83	0.01	100	57	25	18	
02TX	m^3 Transport		5 544	0.06	100	57	25	18	
02	**EARTH WORK**								
03AX	kg Concrete reinforcement				0				
03CP	m Pile		130	0.87	100			20	35
03EX	m^2 Cast-in-place Concrete				0				
03HA	m^3 Reinforced concrete		212	0.72	100			20	35
03HM	m^3 Concrete		660	0.26	100			20	35
03HX	m^3 Concrete foundation		160	1.00	100			20	35
03	**FOUNDATIONS**								
04EA	u Catch basins		84	0.75	100				
04EC	m Collectors		82	0.17	100				
04VB	m Down pipe				100				
04	**WATER DISPOSAL**								
05AX	kg Structural steel				0				
05FX	m^2 Concrete slab		5 638	0.30	100				
05HA	kg Steel reinforcement				0				
05HE	m^2 Concrete cast				0				
05HH	m^3 Reinforced concrete				100				
05	**STRUCTURES**								
06BX	m^2 Concrete blocks				0				
06DX	m^2 Wall chambers		5 763	0.13	100				
06DY	m^2 Wall partitions		4 941	0.07	100				
06LX	m^2 Exterior bricks		639	0.15	100				
06LY	m^2 Interior bricks		394	0.14	100			100	
06	**ENCLOSURES**								
07HX	m^2 Horizontal roofs		524	0.19	100				
07IX	m^2 Inclined roofs			0.35	100				
07	**ROOFS**								
08CX	m^2 Radiators				0				
08CY	m Pipes				0				
08EC	m Circuits		1 855	0.30	100				
08ED	m Derivations		336	0.03	100				
08EL	u Light points		48	1.00	100				
08ET	u Sockets		576	014	100				

(Table 4) contd….

Code	Description	Base	Q	Dg	Total	T_1	T_2	T_3	T_4
08EP	m Ground connection		2	0.55	100				
08FC	m Hot water pipe		192	0.05	100				
08FD	u Drains		48	0.12	100				
08FF	m Cold water pipe		144	0.06	100				
08FG	u Tap		48	0.38	100				
08FS	u Bathroom appliances		48	0.43	100				
08FT	u Thermos / heaters			0.78	100				
08	**INSTALLATIONS**								

Table 5. The work schedule in terms of complex quantities for the first three chapters (II).

Code	Description	Base	Q	Dg	Total	T_1	T_2	T_3	T_4
09AX	m^2 Acoustic insulation				0				
09TX	m^2 Thermal insulation				100				30
09	**INSULATION**								
10AA	m^2 Tiling		9 690	0.09	100				
10CE	m^2 Plaster		14 294	0.04	100				
10CG	m^2 Whitewash		4 377	0.03	100				
10SX	m^2 Screed		610	0.09	100				
10SY	m^2 Floors		874	0.11	100				
10TX	m^2 Ceiling		302	0.06	100				
10RX	m Finishing		350	0.14	100				
10	**FINISHES**								
11AX	m^2 Steel frames		529	0.51	100				
11LX	m^2 Aluminium			0.63	100				
11MX	m^2 Wood				0				
11MA	m^2 Closets				0				
11MP	m^2 Wooden doors		86	0.53	100				
11SB	m Bannister		156	0.47	100				
11SP	m^2 Shades		82	0.26	100				
11SR	m^2 Safety bars			0.27	100				
11	**CARPENTRY**								
12XX	Glass		6 418	0.10	100				
12	**GLASS AND POLYESTER**								
13EX	m^2 Exterior paint		27 674	0.03	100				
13IX	m^2 Interior paint			0.03	100				
13	**COATING**								

Table 6. Cost comparison table, during Period T_4 (I).

Code	Description	T_4		Deviations	
		Actual (C_R)	Plan (C_P)	C_R-C_P	V^C
01A	Bricks				
01C	Foundations				
01E	Buildings				
01L	Installations				
01K	Carpentry and security				
01Q	Roof				
01R	Finishes				
01S	Water disposal				
01T	Preparation works	631	631	0	0.0
01X	Structures				
01W	Others				
01	**DEMOLITION**	631	631	0	0.0
02A	Excavations	2 027	2 027	0	0.0
02P	Pads	4 536	39 548	-35 012	-27.8
02R	Refill and compacting	105	454	-349	-0.3
02T	Transport	39 547	74 128	-34 580	-27.5
02W	Others				
02Z	Trenches	1 339	105	1 235	1.0
02	**EARTHWORK**	47 556	116 262	-68 706	-10.9
03A	Steel works				
03C	Special foundations				
03E	Concrete cast				
03H	Concrete	74 127	40 886	33 241	26.4
03W	Others				
03	**FOUNDATIONS**	74 127	40 886	33 241	26.4
04C	Hanging pipelines				
04E	Underground pipelines	9 995	0	9 995	7.9
04V	Vertical pipelines				
04W	Others	708	0	709	0.6
04	**WATER DISPOSAL**	10 703	0	10 704	4.3
05A	Steel				
05F	Concrete slab	54 148	0	54 149	43.1
05H	Reinforced concrete				
05M	Wood				
05W	Others	6 520	0	6 520	5.2

(Table 6) contd….

Code	Description	T_4		Deviations	
		Actual (C_R)	Plan (C_P)	C_R-C_P	V^C
05	**STRUCTURES**	60 669	0	60 669	24.1
06A	Arches and vaults				
06B	Concrete blocks				
06C	Stone blocks				
06D	Brick partitions				
06L	Brick walls				
06P	Prefabricated				
06W	Others				
06	**PARTITIONS**				
07H	Horizontal roof				
07I	Sloping roof				
07W	Others				
07	**ROOFS**				

Table 7. Cost comparison during Period T_4 (II).

Code	Description	T_4		Deviations	
		Actual (C_R)	Plan (C_P)	C_R-C_P	V^C
08C	Air conditioning				
08E	Electricity				
08F	Water				
08L	Gas				
08M	Electro-mechanic appliances				
08P	Fire protection				
08V	Audio-visual				
08S	Hygiene				
08W	Others				
08	**INSTALLATIONS**				
09A	Acoustic				
09I	Waterproofing	454	36	418	0.3
09T	Thermal				
09W	Others				
09	**INSULATION**	454	36	418	0.3
10A	Cladding				
10C	Continuous				
10L	Lightweight				
10P	Stairs				

(Table 7) contd….

Code	Description	T_4		Deviations	
		Actual (C_R)	Plan (C_P)	C_R-C_P	V^C
10S	Floor	15 510	0	15 511	12.3
10T	Ceiling				
10W	Others				
10	**FINISHES**	15 510	0	15 511	12.3
11A	Steel				
11L	Alloys				
11M	Wood				
11S	Security and safety				
11W	Others				
11	**CARPENTRY**				
12L	Glass: large format				
12V	Glass: small format				
12W	Others				
12	**GLASS AND POLYESTER**				
13E	Exterior				
13I	Interior				
13W	Others				
13	**COATING**				
14M	Furniture				
14W	Others				
14	**DECORATION**				
15A	Sewers				
15C	Safety signalling				
15E	Electricity				
15G	Gas				
15J	Gardening				
15M	Earthmoving				
15P	Pavement				
15S	Water supply				
15T	Telephone				
15V	Furniture				
15W	Others				
15	**URBANIZATION**				

Tables **6** and **7** take place during period 4 (T4) which corresponds to the 4th month since the project started. The indicators for each sub-chapter, column "V", are determined using equation (8). Equation (10) is applied to determine the indicator average value within a chapter, and finally, for the whole project, equation (12) is applied. Identical calculations are performed with the "complex quantities" using equations (9), (11) and (13).

The next step, for the time period, is the completion of a simple report, as shown in Table **8**. In the table, those indicators divided by the standard deviation which are equal to or bigger than ±1.5 are bold-faced, thereby highlighting processes outside the control limits.

The report can be easily understood by the project manager, (normally in charge of several projects), who only needs to look at the indicators in the cost and quantities to obtain the required information. Comments on the indicators are made in the report table, and recommendations can then be defined. Possible comments or recommendations will be kept simple, such as: for positive values, the process is slightly ahead of schedule, strongly ahead of schedule; or for negative values, the concrete was not delivered on time, the earthwork is slower than expected.

Once the report is completed, the next step is to graphically represent the indicators and identify the processes that are off target and susceptible to correction. The statistical variables are determined for each specific period of time. Figs. (**2**, **3**) represent the indicators of each chapter up to period T_4, of cost and quantities, respectively. The indicators are calculated using equations (12) and (13) divided by the standard deviation of the sample during the corresponding period. An indicator, which is higher than 1.5, signifies that the cost or quantity has exceeded that of 86% of the population during the period, and is therefore considered in need of corrective action.

In Fig. (**2**), where the indicators for the first 4 months are represented, all indicators higher than 1.5 need to be checked and controlled. For example, it can be seen that *Chapter*

Table 8. Report of the production carried out in terms of cost and quantity.

REPORT					
PROJECT: 309 dwellings					
Location: Seville, Spain			Expected duration: 22 months		
Built surface: 46 968 m^2			Period: T4		
SITUATION:					
SCHEDULE:					
Third revision and re-scheduling					
Indicators /Standard Deviation					
Chapter	**V^C/S^C**	**V^Q/S^Q**	**Chapter**	**V^C/S^C**	**V^Q/S^Q**
01. Demolition	0		10. Finishes	0.66	1.04
02. Earthwork	-0.58	0	11. Carpentry	0	0
03. Foundations	1.41	0.52	12. Glass	0	0
04. Water disposal	0.23	0.28	13. Coating and tiles	0	0
05. Structures	1.29	**3.56**	14. Decoration	0	0
06. Partitions	0	0	15. Urbanization	0	0
07. Roofs	0	0			
08. Installations	0	0			
09. Insulation	0.02	0			
Completed work: 209 652.84 €			Control limit (1.5S)		
COMMENTS:					
Code		**Description**		**Comment**	
03H		Concrete		Strongly ahead of schedule	
05F		Concrete pad		Strongly ahead of schedule	
10S		Floor tiles		Strongly ahead of schedule	
RECOMMENDATIONS					
A new schedule needs to be defined because the construction is being performed faster than originally planned.					

C03: Foundation has been significantly off schedule since month 2 (T_2). The chapter needs to be checked and rescheduled. The same also happens with *Chapter C04, Water disposal*, during month 4 (T_4).

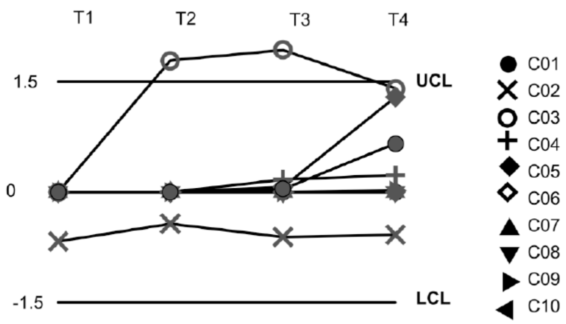

Fig. (2). Statistical process control of project cost.

On the other hand, the control chart for quantities (Fig. **3**) shows slightly different behaviour since market cost fluctuations are not taken into consideration and only the quantities of work completed are considered. Moreover, the indicators are determined with respect to the total corrected quantities (by means of the D_g correcting factor) in the project and not with respect to the total project cost. *Chapter 03 Foundation* is off target during month 2 because the work started earlier than planned, but this deviation is not significant in month 3 (T_3) and 4 (T_4), since *Chapter 06* is the important quantity in the project, even though it is not an important cost in (Fig. **2**).

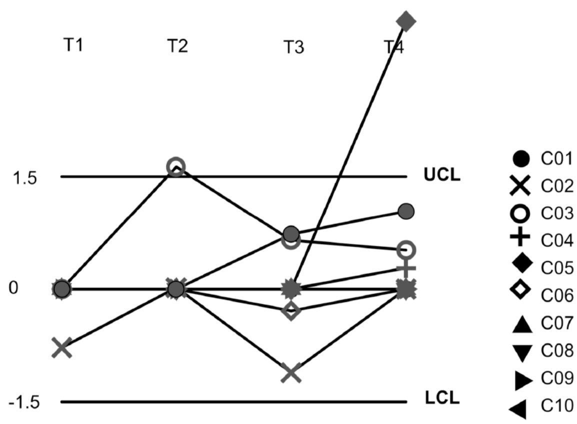

Fig. (3). Statistical process control of project quantities.

The tool improves the control of cost and schedule, especially at manager level, since a simple general graph indicates the overall construction site behaviour or that of several construction sites at the same time. The most important contribution of the control chart, as in any application of SPC, is that it provides a simple visual support to managers; this is especially significant under a multi-project management environment, since the representation remains in an identical form for all the projects. The same WBS is used, the indicators are dimensionless and independent of the project size, and the control limits can be set to identical values in all project graphs. The SPC general rules apply, as in industrial processes where SPC is commonly used: when three points are under the control limit but with increasing deviations or a major fluctuation takes place, then the process is considered out of control and this can be visually detected.

CONCLUSION

To guarantee the effectiveness of the model, the following objectives are met:

1. The model implementation is simple and quick; a commonly used spread sheet is the only software needed.
2. The information required in order to use the model is easy to obtain and causes no obstacles to the daily workload of the data collector.
3. The results are reliable since they are based on the cost data, which is a contractual commitment, and are represented by sensitive indicators that are easy to understand: mean and standard deviation.
4. The structure of the results facilitates rapid understanding of the general situation and also allows an in-depth analysis of the causes.
5. The cost of implementing the system is significantly lower than the savings provided by its use.

Future work involves the development of the classification system so that it includes the control of construction projects other than that of dwellings, such as libraries, gymnasiums, and school and college buildings. Furthermore, another alternative to this approach could involve the organization of the budget and activities through a process classification system instead of the present cost classification system.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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Declared none.

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