INTERNATIONAL JOURNAL OF OPTIMIZATION IN CIVIL ENGINEERING
Int. J. Optim. Civil Eng., 2012; 2(3):407-422

COMPARATIVE COSTS OF THE PRODUCTION, TRANSPORT AND ASSEMBLY STAGES OF PRESTRESSED PRECAST SLABS USING GENETIC ALGORITHMS

V. C. Castilho[*, †] and M.C.V. Lima
School of Civil Engineering, Federal University of Uberlândia, Av. João Naves de Ávila, 2121, Bloco 1Y, Campus Santa Mônica, Uberlândia, MG, Brasil

ABSTRACT

In the precast structures, optimization of structural elements is of great interest mainly due to a more rationalized way that elements are produced. There are several elements of precast prestressed concrete that are objects of study in optimization processes, as the prestressed joist applied in buildings slabs. This article inquires into cost minimization of continuous and simply supported slabs, formed by unialveolar beams and prestressed joist, using Genetic Algorithms (GAs). Comparative analyses of the final costs were made for these two precast elements, previously investigated in Castilho [1] and Castilho [2]. Furthermore, parcels of cost function were analyzed for the cases of prestressed joist and unialveolar beam, and the results show that the production stage of the element matches the largest part of the cost function. Also, although the prestressed joist is more economical, unialveolar beam reaches the market to compete with the other precast elements for slabs.

Received: 10 April 2012; Accepted: 14 July 2012

KEY WORDS: genetic algorithm; prestressed joists; unialveolar beams; cost minimization; continuous slabs

1. INTRODUCTION

The production process of precast concrete structures consists of transitory stages ranging from the implementation of these elements to the completion of the definitive connections.

[*]Corresponding author: V.C. Castilho, School of Civil Engineering, Federal University of Uberlândia, Uberlândia, Brasil.
†E-mail address: castilho@feciv.ufu.br (V.C. Castilho)

In the case of precast from factory, those stages consist of the elements fabrication, the transport in the plant, the external transport from the manufacturing area to the assembly site, the placement of the elements in definitive site and finally, the implement of connections between the elements and the local structure [3]. Such stages are part of the problem description and may present demands more unfavorable than cast-in-place concrete structures.

The slabs made of precast joists consist of precast elements (ribs), filling elements such as hollow blocks or expanded polystyrene (EPS), which are placed over the precast concrete, and later on the concrete cast-in-place, for cover molding. The structural behavior of slabs made of precast joists, are similar to those of the one direction reinforced slabs (unidirectional slabs), with resistant section composed by the precast part and by the concrete cast-in-place.

For the solution of problems related to the optimization of precast concrete elements, it is required to, initially define an objective function (the cost function), the restrictions for the analyzed problem (limit states: ultimate and serviceability) and the lateral restrictions (upper and lower limits of each variable). The cost function normally used in the optimization process, must represent the entire manufacturing process of the elements, from plant production to their effective connection to the main frame. To evaluate the problem concerning the optimization of precast concrete structures, all stages costs should be part of problem representation.

In order to design and produce this type of elements the following guidelines must be considered:

- Transitory phases — individual joists should be checked at all stages (i.e., stripping, transportation storage and erection).
- Serviceability limit state — the normal stresses should be checked to avoid cracks and the deflection limit.
- Ultimate limit state — the strength for bending moment and strength for shear force.

The choice of prefabricated slabs represents an alternative for work quality and speed. The prestressed concrete joists and unialveolar beams are produced in large prestressing tracks, by means of fixed forms or slip forms, similar to the alveolar panel.

The handling of these elements is done without the aid of any equipment. The transport is performed by trucks and the assembly is accomplished manually. It is also used a scaffold support to receive the ribs, which remains until the concrete cast hardens. It is recommended the use reinforcement in the cast-in-place concrete, placed in both directions, which is called the complementary reinforcement.

In the structural design of those slabs, the demands evaluation is usually done by considering the slab as a beam, simply supported or a continuous one, as the case. The unialveolar slab is composed of unialveolar beams assembled in the building structure, over which it is thrown the cast-in-place reinforced concrete. That type of alveolar beam allows two possible arrangements according to the structural and architectural requirements of each project. It should be noted that when assembled with inter-axis, there is a strong similarity to the arrangements of prestressed joists. This one is largely spread in the Brazilian market, allowing slabs with spans of around 10m.

Although the unialveolar beam is quite new in the market, its application is confirmed to be an interesting and viable option in the implementation of prefabricated slabs. This slab is extremely economical if compared to alveolar slabs, although it reaches higher final height.

In this paper, it will be reviewed the costs minimization of simply supported slabs formed by unialveolar beams and continuous and unidirectional slabs formed by prestressed joists and unialveolar beams using a heuristic method, the Genetic Algorithm (GA). Later, some comparisons have been projected regarding the unialveolar beams and prestressed joists, in order to verify if such slabs formed by these elements are economical when compared to the joists previously analyzed in Castilho [4-5].

2. SLABS FORMED BY PRECAST ELEMENTS

The choice of prefabricated slabs represents quality and speed to the build process. Presently, there is the emergence of new technologies about concrete extrusion associated to design knowledge in order to develop new types of slabs [6].

The unialveolar slab is a new application that presents as a viable alternative in industrial building and offices and will be the aim of this paper. The system was developed and patented in 2003 by *R4 Tecnologia Aplicada*[1] and *Esesp*, which license and commercialize the technology and equipment, with a pilot plant installed in São Paulo. Unialveolar slabs are similar to traditional hollow core slabs, since they are manufactured by extrusion as prestressed elements.

The slab is composed by unialveolar beams bearing on the structure with a cover concrete, armed with conventional reinforcement. This beam type allows two possible arrangements according to the structural and architectural needs of each project. It should be noted that assembly has a strong resemblance to the arrangement of prestressed joists.

The unialveolar beam geometry has notches on its sides (Figure 1), in order to assist the incorporation of the cast-in-place concrete. The arrangement with inter-axis leads an extremely light slab, with a large percentage of voids in the slab structure. This section, together with the cast-in-place cover concrete in the unialveolar beams, performs an important role in structural calculation, resulting in a lighter slab, around 40% and 50% less steel prestressed/m² compared to the alveolar slab.

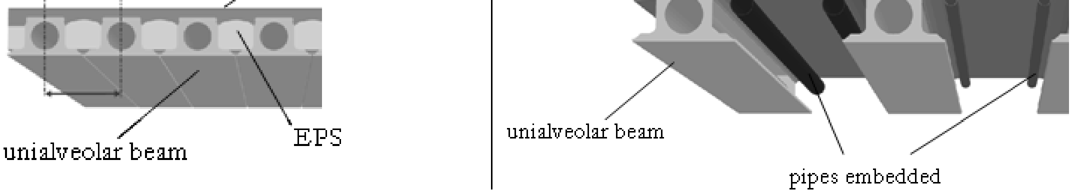


Figure 1. Different geometries for the unialveolar beam [6]

[1] Site accessed at 5/31/2005 - www.r4tecno.com.br

3. GENETIC ALGORITHM

Genetic Algorithm (GA) is a search and optimization method that uses concepts of Genetics and is based on the mechanisms of populational evolution. The GA was inspired on the natural selection and survival of the fittest established by Charles Darwin's book "The Origin of Species", published in 1859. According to this principle, in any given population of individuals, those with “good” characteristics have greater chances for survival and reproduction while less “capable” individuals tend to disappear during the evolutionary process.

The GA simulates biological evolution by means of a multidirectional search within the space of potential solutions for the problem. This algorithm maintains a constant number of potential solutions (population), modifying the population in each successive generation so that “good” solutions can “reproduce” and pass on to the next generation, while “bad” solutions are discarded. GA generally uses probabilistic transition rules to select some solutions for reproduction and others for discard. The basic principles of GA basic were established by Holland [7] and are found in many references in the literature [8-13].

A typical GA uses three operators, the selection one, the mating one and the mutation one, leading the population (through several generations) in the direction from the convergence point to the global optimum point. After the application of selection, mating and mutation, a new population is formed. The process repeats until a certain number of generations have been created, or else, some other stop criterion is met. Several studies in the area of structural optimization were developed using the GAs technique [14-18].

4. COSTS DEFINITION FOR PRECAST ELEMENTS

When defining the cost function, parcels of fabrication, external transport and assembly stages of precast elements are considered [14]. Basically, the costs of the entire process consist of stages ranging from the fabrication of these elements to the effectiveness of the final connections. They are as follows:

- fabrication costs: the costs involved in the manufacture of precast elements and it refers to the costs of raw material, additional costs and administrative overhead.
- external transport costs: it involves transport costs from the plant to work site.
- assembly costs: the costs involved in fabrication the elements and correspond to the costs of assembling the truss-framed joist, the cast-in-place concrete costs, negative and adicional reinforcement costs and administrative costs.
- additional costs: involve the costs related to the operation after molding and prior to the forwarding to the work site. The additional cost is the sum of labor costs and equipment: manual labor to handle the equipment, curing, transport, storing and equipment for curing, energy, fuel and fork-lift.
- Administrative costs: include costs with engineers, supervisors, receptionists, project implementation, social charges, advertising, energy, taxes, rents, insurance, office supplies, maintenance costs, freight, fuel, depreciation and return on investment. Initially, the administrative overhead corresponds to 10% of the raw materials and

additional costs.

4.1. Costs of slabs formed by unialveolar beams

The costs used for the analysis, considered the same values adopted by Castilho [1-2]. The values of the final costs for the unialveolar beam are presented in Table 1. All prices are given in Brazilian Real (R$). The conversion rate is 1.00USD=1.70BRL and 1.00EUR=2.79BRL (in October 16th, 2010).

Tabel 1. Costs of unialveolar beam.

			Material	**Manual labor**	**Equipment**
PRODUCTION	Cost of raw material	Concrete cost (R$/m^3)	$(24.75f_{ck} + 74.25)$	4.40	8.35
		Reinforcement cost (R$/kg)	2.95	0.295	0.07
		EPS cost (R$/m^3)	2.00	1.00	1.00
	Additional cost (R$/m^3)		-	4.40	1.67
	Administrative cost (R$/m^3)		10% of the cost of raw material and additional		
TRANSPORT	Transport cost (R$/m^3)		52		
ASSEMBLY	Assembling cost (R$/m^3)		-	11.96	9.79
	Cast-in-place concrete cost (R$/m^3)		$(24.75f_{ck,cast} + 74.25)$	104.20	1.67
	Administrative cost (R$/m^3)		20% of the assembly cost (cast-in-place concrete)		

4.2. Costs of slabs formed by prestressed joists

The costs used in the analysis, considered the same values adopted in the paper presented by Castilho [1-2]. The values of the final costs for the prestressed joist are shown in Table 2. All prices are given in Brazilian Real (R$). The conversion rate is 1.00USD=1.70BRL and 1.00EUR=2.79BRL (in October 16th, 2010).

Table 2. Prestressed joist costs.

			Material	Manual labor	Equipment
PRODUCTION	Cost of raw material	Concrete cost (R$/m^3)	$(24.75f_{ck} + 74.25)$	4.40	8.35
		Reinforcemet cost (R$/kg)	2.50	0.25	0.07
		EPS cost (R$/m^3)	2.00	2.20	1.00
	Additional cost (R$/m^3)		-	4.40	1.67
	Administrative cost (R$/m^3)		10% of the cost of raw material and additional		
TRANSPORT	Transport cost (R$/m^3)		52		
ASSEMBLY	Assembling cost (R$/m^3)		-	11.96	9.79
	Cast-in-place concrete cost (R$/m^3)		$(24.75f_{ck,cast} + 74.25)$	104.20	8.35
	Complementary reinforcement cost (R$/m^3)		1.13	0.295	-
	Administrative cost (R$/m^3)		20% of the assembly cost (cast-in-place concrete)		

5. COST MINIMIZATION OF PRECAST ELEMENTS BY GENETIC ALGORITHMS

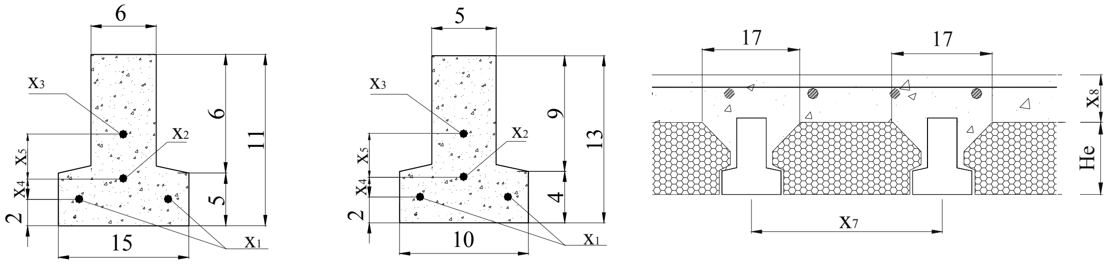
5.1. Loads and types of precast elements

The optimization of prestressed concrete joists and unialveolar slabs was developed considering that the forces taken into account in the design were distributed uniformly along the element, and consisted of the concrete's dead weight (γc=25 kN/m^3), a permanent load of 0.5 kN/m^2 and a live load of 3.0 kN/m^2.

The final section of the slab formed by the unialveolar beam is shown in Figure 2. The slab was completed with EPS and cast-in-place concrete. The design of one unialveolar slab is described in Castilho [14] for alveolar slabs.

Figure 2. Slab section formed by unialveolar beam

The cross sections of the analyzed prestressed joists (type 2 and type 3) are shown in Figure 3, together with the concrete strength of the joist. The design is described in details, in Castilho [14]. The section of the prestressed joist type1 was analyzed in Castilho [14], and it will not be the focus of this paper.



a) joist type 2 (f_{ck} = 39MPa)

b) joist type 3 (f_{ck} = 45MPa)

c) cross section of the slab

Figure 3. Cross section of joists and slab (unit in 10^{-2}m)

5.2. Case of the simply supported unialveolar slab

The optimization problem refers to the minimization of the total cost function, of a simply supported slab with unialveolar beam, for spans of 2m, 3m, 4m, 5m and 6m. The variables involved in defining the cost function were the height of the unialveolar slab, the amount of prestressed reinforcement, the concrete strength of the slab, the height of the cast-in-place concrete, the cast-in-place concrete strength and the inter-axis distance.

5.2.1. Total cost function

Aiming to obtain the function that represents the total cost of production, considering the fabrication, transport and assembly stages, the various costs were added and the final expression of the function is given by Equation (1):

$$f(x_i) = 1{,}728 \cdot \frac{15 + (x_1)^2 - \pi \cdot \left(\frac{x_1}{2} - 2\right)^2}{x_6} + 0{,}0624 \cdot x_6 + 1{,}473 \cdot x_4 + 0{,}012 \cdot (24{,}75 \cdot x_5 + 74{,}25) \cdot x_4 + \quad (1)$$

$$+ 0{,}011 \cdot (24{,}75 \cdot x_3 + 74{,}25) \cdot \frac{15 + (x_1)^2 - \pi \cdot \left(\frac{x_1}{2} - 2\right)^2}{x_6} + 2{,}407 \cdot x_2$$

where:

x_1 – unialveolar slab height (cm)
x_2 – prestressing reinforcement (cm^2)
x_3 – strength of the unialveolar slab (kN/cm^2)
x_4 – height of the cast-in-place concrete (cm)
x_5 – strength of the cast-in-place concrete (kN/cm^2)
x_6 – distance of the inter-axis (cm)

Further details regarding the final expression of the function are described by Castilho [14]. The unialveolar slab optimization problem therefore consists of the problem of minimization of $f(x) = (x_1, x_2, x_3, x_4, x_5, x_6)$, subject to the restrictions of the service limit and ultimate limit states. In addition to these restrictions, the continuous variables should satisfy the lateral restrictions presented in Table 3. Further details are described by Castilho [14].

Table 3. Lateral restrictions for the variables

$0.12 \le x_1 \le 0.40$ (m)	$0.04 \le x_4 \le 0.10$ (m)
$10^{-4} \le x_2 \le 10^{-3}$ (m^2)	$15 \le x_5 \le 50$ (MPa)
$30 \le x_3 \le 60$ (MPa)	$0.30 \le x_6 \le 0.60$ (m)

5.2.2. Description of experiments and analysis of results

In this section, the search for the solution for the problem of cost optimization via GA is studied using the following characteristics: elitism (1 individual), population of 100 individuals, representation by real numbers, uniform mating, tournament selection strategy, stopping criterion defined in 1000 generations and the final results represent the average values achieved in 10 runs. Table 4 presents the final values of project variables, as well as the cost function for spans of 2m, 3m, 4m, 5m and 6m.

Table 4. Values of the variables and of the cost function for several spans - unialveolar slab

	Cost Function ($R\$/m^2$)	**x_1 (m)**	**x_2 (10^{-4} m^2)**	**x_3 (MPa)**	**x_4 (10^{-2} m)**	**x_5 (MPa)**	**x_6 (10^{-2} m)**
L = 2m	29.64	0.18	1.06	33.4	4.04	30.3	59.32
L = 3m	31.43	0.23	1.07	30.9	4.07	15.7	59.47
L = 4m	34.81	0.26	1.13	30.8	4.07	15.6	59.50
L = 5m	41.90	0.31	1.48	33.6	4.04	16.2	59.56
L = 6m	51.23	0.38	1.92	35.7	4.05	19.4	58.78

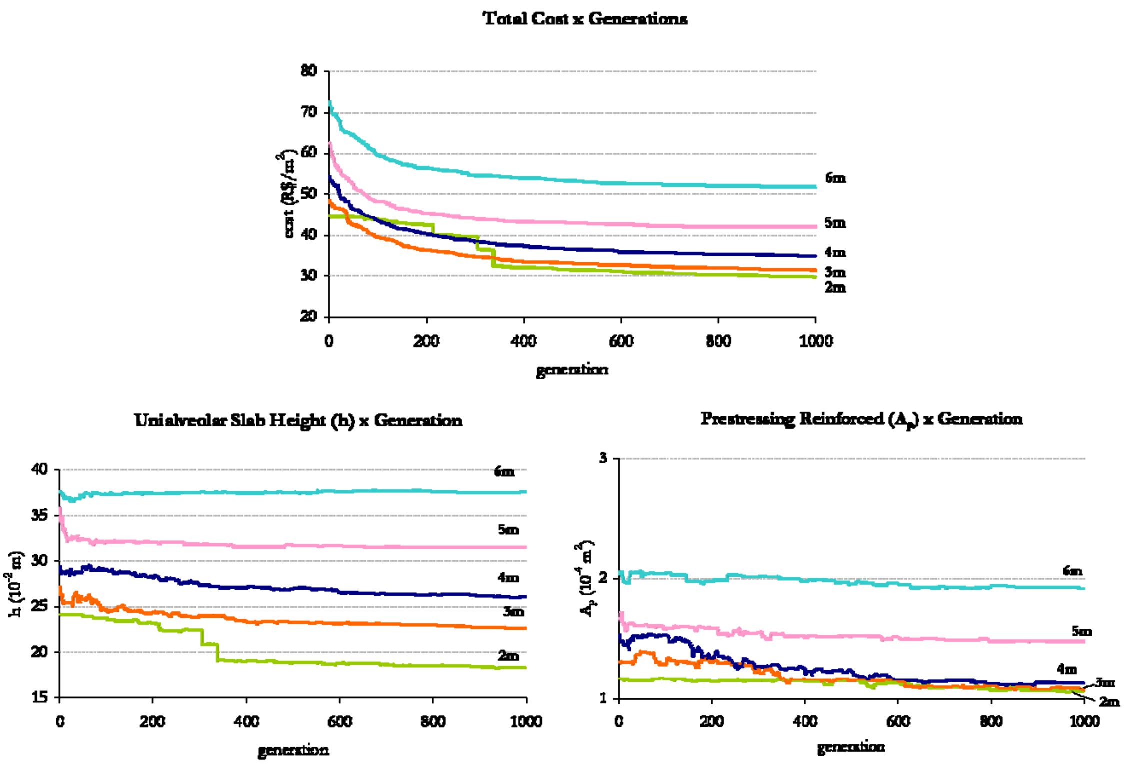
x_1 – unialveolar slab height, x_2 – prestressing reinforcement, x_3 – concrete strength of the unialveolar slab, x_4 – height of the cast-in-place concrete, x_5 – strength of the cast-in-place concrete, x_6 – inter-axis distance.

From the results, it is noticed that numbers tend to remain very close to the variables: concrete strength of the slab, the cast-in-place concrete height and inter-axis distance. For the remaining ones, the values found by the optimization were quite different upon the analysis of different spans. The concrete area does not change with inter-axis increasing or decreasing. For a wider span, it is confirmed that there is an increase of the concrete strength of the beam. Moreover, with span increasing, there is a requirement for an increase of slab strength, obtained by increasing the strength of the cast-in-place concrete.

In order to evaluate the behavior of all variables in each generation, the Figure 4 show the results of the design variables and the cost function for different spans in 1000 generations.

In Figure 4, it is possible to notice that in the first generations the values obtained show a slight disturbance, tending to stabilize short after. It should be noted that all analysis done in several spans converged to the use of any type of scaffold supports. Analyzing the contents in Table 4 and Figure 4, it can be concluded that:

- There is an increase in the height of the unialveolar slab when the span is increased. This increase provides an increase in the prestressing reinforcement;
- Except for the slab with 2m of span, every time the span is increased, the concrete strength of the unialveolar slabs raises as well as the cast-in-place concrete strength. It can be concluded that by increasing the span, there is a demand to increase slab strength, also achieved by increasing the cast-in-place concrete strength;
- There is a slight reduction of the inter-axis distance, noticed in the slab with a length of 6m. Increasing height of table compression, a shorter distance between axis is achieved and, consequently, a smaller area of concrete. This decrease in the concrete area results in a lower cost of cast-in-place concrete.



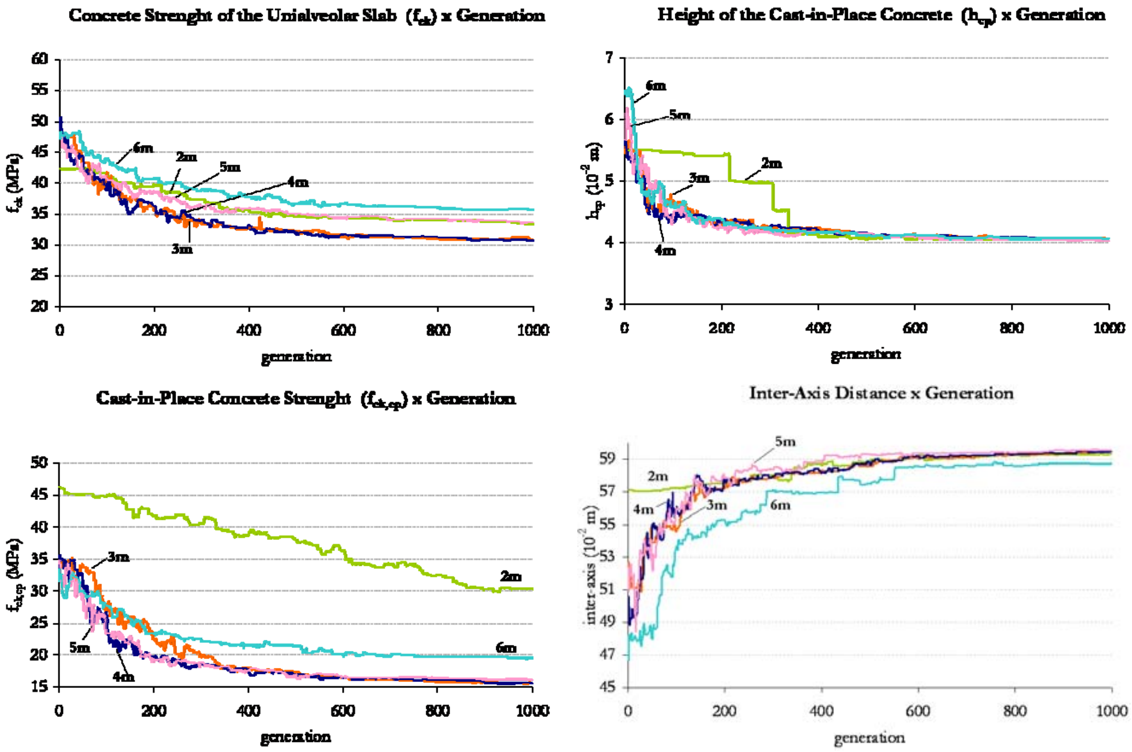


Figure 4. Function cost and the variables values for each span in 1000 generations

5.2.3. Comparing unialveolar slab and simply supported prestressed joist

A comparative cost analysis, between the prestressed joist (type 2) and the unialveolar beam considering the case of simply supported slabs, was conducted and the results were presented in Figure 5. For the span of 3m, the prestressed joist is about 10% cheaper. Meanwhile, for the span of 4m, the prestressed joist is almost 2% more expensive if compared to the unialveolar beam.

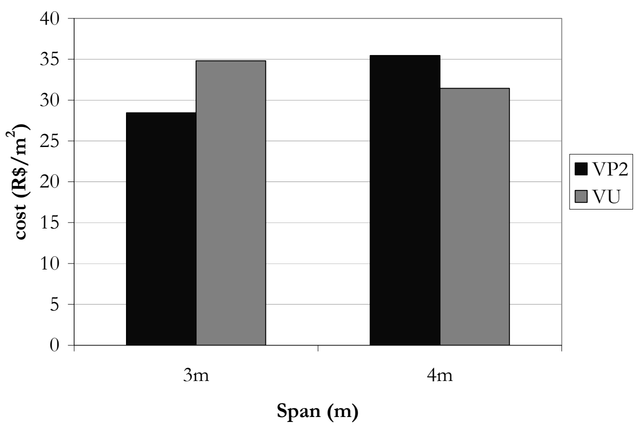


Figure 5. Comparing costs between unialveolar slab and simply supported prestressed joist

5.2.4. Continuous slab case: comparison between the prestressed joist and unialveolar beam

In order to assess cases involving continuous slabs, analysis were made for two elements: prestressed joist and unialveolar beam, both evaluated in Castilho [1-2], respectively. Figure 6 shows the static layout of the unialveolar and the prestressed slabs considered in the analysis: total span of 8m (4m - 4m) and total span of 12m (6m - 6m).

The variables considered in the unialveolar beam case, were the height of the slab, the amount of prestressed reinforcement, the strength of slab concrete, the height of cast-in-place concrete, the strength of cast-in-place concrete, the inter-axis distance and the redistribution degree. For the case of prestressed joist, the variables were the reinforcement of prestressing, the height of the reinforcement in each element, the strength of cast-in-place concrete, the distance of the inter-axis, the height of the concrete cover (cast-in-place) and the redistribution degree.

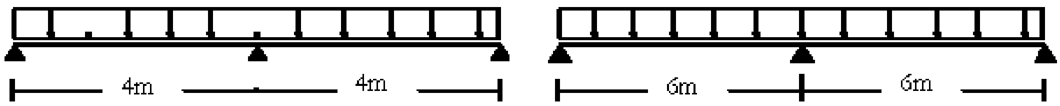


Figure 6. Static layout (span of 8m and 12m)

5.2.5. Total cost function

Aiming to obtain the function that represents the total cost of production, considering the stages of fabrication, transport and assembly, the various costs were added and the final expression of the cost function is presented for each element. For the unialveolar joist the cost function is given by Equation 2, for the prestressed joist type 2 by Equation 3, and finally, for the prestressed joist type3 by Equation 4. Further details regarding the final expression of the function are described by Castilho [14].

$$f(x_i) = 1.728\frac{15+(x_1)^2-\pi\left(\frac{x_1}{2}-2\right)^2}{x_6} + 0.0624x_6 + 1.473x_4 + 1.168A_{neg} + 0.012(24.75x_5 + 74.25)x_4 + \qquad (2)$$

$$+0.011(24.75\cdot x_3 + 74.25)\frac{15+(x_1)^2-\pi\cdot\left(\frac{x_1}{2}-2\right)^2}{x_6} + 2.407x_2$$

where:

x_1 – unialveolar slab height (cm)

x_2 – prestressing reinforcement (cm^2)

x_3 –unialveolar slab strength (kN/cm^2)

x_4 – height of cast-in-place concrete (cm)

x_5 - strength of cast-in-place concrete (kN/cm^2)

x_6 – inter-axis distance (cm)

A_{neg} – value of the negative reinforcement achieved during calculation (cm^2)

$$f(x_i)=\frac{533.45}{x_7}+1.552x_8+1.168\frac{\left[-2.22L+8.879-15.68\left(\frac{11}{10240}x_7x_8+\frac{11}{32000}x_7H_e\right)L+0.0784x_7x_8\right]}{H_e+x_8-2.0}$$
$$+1.1687\frac{\left[0.0251H_ex_7+1.1x_7-0.549x_7L(0.5-0.125x_9)\right]}{H_e+x_8-2.0}+0.0682x_7+0.012x_8\cdot(24.75\cdot x_6+74.25)$$
$$+\frac{335.775(x_1+x_2+x_3)}{x_7}+\frac{0.0158x_7}{(x_1+x_2+x_3)}+1.0 \quad (3)$$

$$f(x_i)=\frac{420.36}{x_7}+1.552x_8+1.168\frac{\left[-1.691L+6.76-15.68\left(\frac{11}{10240}x_7x_8+\frac{11}{32000}x_7H_e\right)L+0.0784x_7x_8\right]}{H_e+x_8-2.0}$$
$$+1.1687\frac{\left[0.0251H_ex_7+1.098x_7-0.549x_7L(0.5-0.125x_9)\right]}{H_e+x_8-2.0}+0.0682x_7+0.012x_8\cdot(24.75\cdot x_6+74.25)$$
$$+\frac{335.775(x_1+x_2+x_3)}{x_7}+\frac{0.0158x_7}{(x_1+x_2+x_3)}+1.0 \quad (4)$$

where:

- x_1 – reinforcement level 1 (cm^2)
- x_2 – reinforcement level 2 (cm^2)
- x_3 – reinforcement level 3 (cm^2)
- x_6 – strength of the cast-in-place concrete (kN/cm^2)
- x_7 – inter-axis distance (cm)
- x_8 – height of the concrete cover (cm)
- x_9 – redistribuition degree

for L = 4m → He = 0.08m; for L = 6m → He = 0.12m

Therefore, the problem of minimizing the production cost of continuous slabs may be synthetized to the minimization problem of f(x) subject to the restrictions of the limit states, ultimate and serviceability, beyond the restrictions presented in Table 5. Further details are described by Castilho [14].

Table 5. Continuous slab lateral restrictions

Prestressed joist		Unialveolar beam	
$3x10^{-5} \le x_1 \le 3x10^{-4}$ (m^2)	$0.30 \le x_7 \le 0.60$ (m)	$0.15 \le x_1 \le 0.40$ (m)	$15 \le x_5 \le 50$ (MPa)
$10^{-5} \le x_2 \le 2.6x10^{-4}$ (m^2)	$0.04 \le x_8 \le 0.10$ (m)	$10^{-4} \le x_2 \le 10^{-3}$ (m^2)	$0.30 \le x_6 \le 0.60$ (m)
$0 \le x_3 \le 10^{-3}$ (m^2)	$0 \le x_9 \le 40$ (%)	$30 \le x_3 \le 60$ (MPa)	$0 \le x_7 \le 40$ (%)
$15 \le x_6 \le 60$ (MPa)		$0.04 \le x_4 \le 0.10$ (m)	

5.2.6. Analysis of results for continuous slabs

Considering the elements used in the search for solution of optimization problems using GA, it is possible to compare the final cost and the variables found for each case of continuous slabs formed by prestressed joists [1] and by unialveolar beams [2]. The comparison results are shown in Table 6.

Table 6. Cost function values for continuous variables for span of 8m and 12m.

Span (m)	Optimization method	H (m)	A_p (10^{-4} m^2)	f_{ck} (MPa)	$f_{ckcover}$ (MPa)	Int. axis (10^{-2} m)	h_{cp} (10^{-2} m)	η (%)	Cost (R$/$m^2$)	A_{neg}	A_{conc} (m^2)
8m	Prestressed joist type 2	0.11	0.995	31.5	20.1	59.06	4.04	36	32.52	8ϕ5.0	0.0113
	Unialveolar beam	0.26	1.000	33.7	15.0	59.84	4.00	39	36.03	2ϕ5.0	0.0316
12m	Prestressed joist type 2	0.11	1.220	42.8	22.3	58.87	4.08	19	35.41	9ϕ5.0	0.0113
	Unialveolar beam	0.28	1.000	41.8	15.1	59.92	4.00	32	39.19	4ϕ5.0	0.0344
8m	Prestressed joist type 3	0.13	1.563	36.6	21.4	59.20	5.96	22	37.18	8ϕ5.0	0.0086
	Unialveolar beam	0.26	1.000	33.7	15.0	59.84	4.00	39	36.03	2ϕ5.0	0.0316
12m	Prestressed joist type 3	0.13	1.357	43.8	15.7	54.14	8.17	34	45.71	7ϕ5.0	0.0086
	Unialveolar beam	0.28	1.000	41.8	15.1	59.92	4.00	32	39.19	4ϕ5.0	0.0344

h – slab height; Ap – prestressing reinforcement; fck – strength of concrete cover; inter-axis – int. axis distance; hcp – height of the concrete cover; η – redistribution degree; Aneg – area of negative reinforcement; Acon – concrete area of the element.

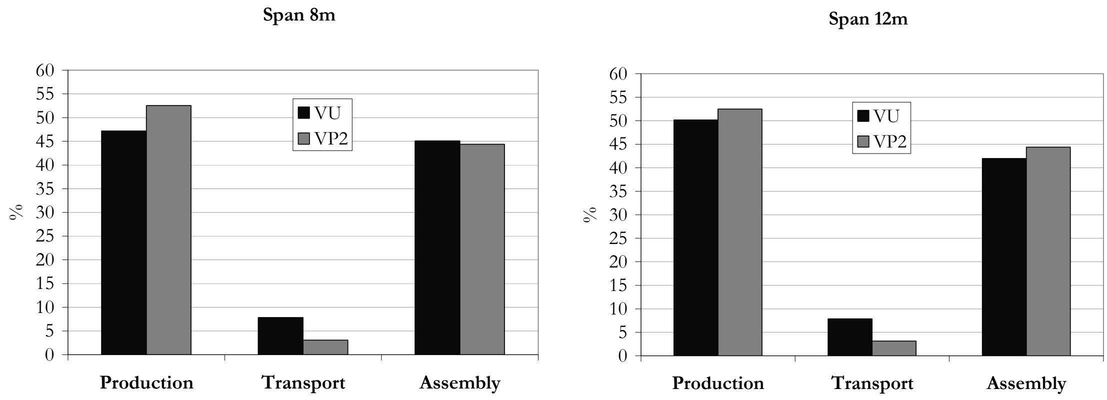
It can be noticed that there are great differences between them. Usually the prestressed joist is cheaper if compared to the unialveolar beam, for two reasons. The prestressed joist has a smaller concrete area, which takes a reduced cost. Moreover, its inter-axis distance is smaller resulting in a smaller section of concrete used in the slab. The advantages of using these two types of elements in slabs are presented in Table 7.

Table 7. Main advantages of the elements

Prestressed joist	Unialveolar beam
• Minor self weight; • Exempt the mold use; • Manual labor reduction for fabrication; • Small number of scaffold supports.	• Prestressing reinforcement lower than the one required by the alveolar one; • Arrangement with inter-axis results in an extremely light slab; • Resulting slab has low self-weight; • Tends to be higher than the alveolar one; • Due to the large empty area, it can be used to inlay building installations.

From Table 7, it appears that each element presents interesting peculiarities with respect to structural performance. It should be noted that each project must incorporate the element according to the function for which it was designed, and the structural evaluation of the set as well.

Comparisons were made on the cost for the spans of 8m and 12m in the case of prestressed joist (type 2) and the unilaveolar beam, to investigate the influence of changes in value, of the total cost function by changing the element type. The results of the different elements for production cost, transport and assembly are shown in Figure 7.



a) Percentage of costs for 8m span b) Percentage of costs for 12m span

Figure 7. Percentage of costs for elements considering 8 and 12 m spans

From Figure 7, it appears that there is no significant change in transport costs when the span is increased. Moreover, it is seen that part of production represents a significant portion of the total cost.

Table 8 shows values in percentage and the amount related to the final cost for the production, transport and assembly obtained for prestressed joist and unialveolar beam considering the span of 8m and 12m.

In Table 8, it appears that there is no significant change in the production stage. Such costs for the 8m span case, practically do not change regardless the type of element. Increasing the span of the slab, those values become representative for the analyzed elements. It is also noticed a large discrepancy in cost referent to transport of the unialveolar beam, reaching more than the double when compared to the prestressed joist. From the results it can be seen that the prestressed joist is really cheaper if compared to the unialveolar beam, as indicated in Table 7.

Table 8. Cost values in percentage in R$/m^2 for each step.

Span	Element	Production (%)	Cost (R$/m^2)	Transport (%)	Cost (R$/m^2)	Assembly (%)	Cost (R$/m^2)
8m	UV	47.18	17.00	7.81	2.81	45.08	16.24
	VP2	52.55	17.09	3.06	1.00	44.39	14.44
12m	UV	50.17	19.66	7.86	3.08	41.97	16.45
	VP2	52.50	18.59	3.13	1.11	44.38	15.71

UV – unialveolar beam; VP2 – prestressed joist type 2

Although the prestressed joist is more economical, the unialveolar beam reaches the market to compete with the precast elements. Being a new element in the construction industry, it is expected that in the future, the unialveolar beam may become a trend as it is now, the prestressed joist.

6. CONCLUSIONS

This study investigated the use of GAs to find the lowest cost solution for slabs made of prestressed joists and unialveolar beams focusing on the following issues: simply supported slabs formed by unialveolar beams for 2m to 7m spans; continuous slabs formed by unialveolar beams and prestressed joists for 8m and 12m spans and comparative analysis of production costs, transport and assembly between the prestressed joist type 2 and the unialveolar beam.

From the results of the cost function and the variables cases of the simply supported unialveolar beams, it is possible to conclude that:

- the numbers tend to remain very close to the variables: concrete strength of the slab, the cast-in-place concrete height and inter-axis distance.
- the height and concrete strength of the unialveolar beam raises proportionately to span increasing, and for wider spans, there is a raise in strength of the cast-in-place concrete in order to increase the slab strength;
- with span increase, the height of the unialveolar slab goes up. This increase provides an raising of prestressing reinforcement;
- except for the slab with span of 2m, increasing the span, the concrete strength value of the unialveolar slab raises and the cast-in-place concrete strength goes up, as well.

From the achieved results of the cost function and the variables for the case of unialveolar beams and continuous prestressed joists, it can be conclude that:

- there is a decrease in the redistribution degree to wider spans and it is required a larger parcel of reinforcement to counter the negative moments;
- it can be concluded that the heuristic tool, the GA, using discrete variables is more effective and robust for the solution of problems with cost minimization of unialveolar beams;
- the comparison between the usage of prestressed joist and unialveolar beams showed that the most economical slabs were formed by prestressed joist.

REFERENCES

1. Castilho VC, Lima MCV. Analysis and cost optimisation of prestressed concrete joists in bem-block floors. *Struct Concrete* 2008; **9**(3): 143−51.
2. Castilho VC, Lima MCV. Uso de variáveis discretas e contínuas na minimização do custo de lajes com vigas unialveolares usando algoritmos genéticos. *In*: *XXIX CILAMCE Congresso Ibero Latino Americano de Métodos Computacionais em*

Engenharia, Maceió, Anais (CD-ROM), 2008.

3. El Debs MK. *Concreto pré-moldado: fundamentos e aplicações*. São Carlos. Projeto EENGE, EESC-USP, 2000.
4. Castilho VC, Lima MCV. Cost optimization of lattice-reinforced joist slabs using genetic algorithm. *Struct Concrete* 2007; **8**(3): 1464–77.
5. Castilho VC, El Debs MK, Nicoletti MC. Using a modified genetic algorithm to minimize the production costs for slabs of precast prestressed concrete joists. *Eng Appl Artif Intell* 2007; **20**: 519–30.
6. Rosauro A. Lajes Unialveolares. *Revista Téchne* 2005; **95**: 61–3.
7. Holland JH. *Adaptation in Natural and Artificial Systems*, University of Michigan Press, Ann Arbor, 1975.
8. Beasley D, Ralph RM, David RB. *An Overview of Genetic Algorithms: Part 2*, Research Topics, University Computing, 1993; **15**(4):170–81.
9. Beasley D, Ralph RM, David RB. *An Overview of Genetic Algorithms: Part 1*, Fundamentals, University Computing, 1993; **15**(2):58–69.
10. Gen M, Cheng R. *Genetic Algorithms and Engineering Design*. New York. John Wiley & Sons, 1997.
11. Goldberg DE. Genetic Algorithms in search, optimization and machine learning. USA, Addison-Wesley Publishing Company, 1989.
12. Lemonge ACC. *Aplicação de algoritmos genéticos em otimização estrutural*. Tese (doutorado) – COPPE, Universidade Federal do Rio de Janeiro, 1999.
13. Michalewicz Z. *Genetic Algorithms + Data Structures = Evolution Programs*. Berlin, Springer-Verlag, 1996.
14. Castilho VC. *Otimização de componentes de concreto pré-moldado protendidos mediante Algoritmos*. São Carlos. Tese (doutorado) – Escola de Engenharia de São Carlos, Universidade de São Paulo, 2003.
15. Castilho VC, El Debs MK, Nicoletti MC. Aplicação de Algoritmos Genéticos na otimização estrutural dos elementos de concreto pré-moldado. *In:XXIX Jornadas Sudamaricanas de Ingenieria Estructural*, Ponta Del Leste, Anais (CD-ROM), 2000.
16. Castilho VC, El Debs MK, Nicoletti MC. Application of Genetic Algorithm for optimization slabs of prestressed concrete joists. *In: 22nd Ibirian Latin-American Congress on Computational Methods in Engineering*, Campinas, Anais (CD-ROM), 2001.
17. Coello CC, Hernández FS, Farrera FA. Optimal design of reinforced concrete beams using Genetic Algorithm. *Expert Syst Appl* 1997; **12**(1): 101–8.
18. Koskisto OJ, Ellingwood BR (1997). Reliability-based optimization of plant precast concrete structures. *J Struct Eng*, *ASCE* 1997; **123**(3): 298–304.