Economic Evaluation of Robotics in Building

by

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1 Introduction

Possible applications of robotics to building construction were examined in [26].It was concluded there that at the present stage of technology the robots can perform four types of tasks which cover a very wide range of building activities:

a. Assembling of large components - steel beams, precast elements etc.

b. Performance of interior finishing operations such as painting, wall papering, welding etc.

c. Covering or applying mechanical treatment to large horizontal surfaces - floors, roofs etc.

d. Spraying or applying mechanical treatment to exterior building walls.

Consequently four different configurations of robots were suggested to perform these activities and their desired features were explored. These robots, described in [26],. will be referred to in the following sections as the *assembling robot*, the *general purpose robot*, and the *finishing robots* (horizontal and vertical).

The benefits usually expected from robots employment are the following:

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a. Direct productivity gains, resulting from partial or complete elimination of human involvement.

b. Ability to operate under conditions especially strenuous or hazardous to humans.

c. Improvement of product quality.

The feasibility of robotization is not difficult to determine in specific cases when the data about robots costs and their expected performance is available. It is very difficult however to reach some general conclusions in the case examined here where the cost of robots to be developed and their performance cannot as yet be established with certainty. The value of robot to user was therefore explored under different aasumptions with regard to its physical performance and the organizational setup within which it would operate.

The benefits of operation under severe conditions can be determined by examining the drop in productivity of human labor and other economic losses (such as expenses associated with work accidents, or schedule extension) which these conditions impose, and can be avoided by robots employment. These losses will be examined and their economic implication in more obvious instances will be explored.

The benefits of improved building quality will be examined only in non quantitative terms due to lack of sufficient data.

2 Costs and benefits of Robotization

The economic feasibility study of robots employment in construction tasks must consider all costs and benefits involved with it. The costs may be classified as follows:

- development costs - include all expenses associated with labor, materials and facilities used for researching, testing and evaluating of the various alternatives of robotic solutions. The development costs, if incurred by the private sector, are included in the ultimate price of the product. If they are financed by the public resources - can be justified by indirect benefits accrued to the society both in terms of general productivity increase, and of applied and basic knowledge acquired during the development process.

- investment costs - include depreciation and the interest on investment. The parameters which must be known for their assessment are the cost of new equipment, its economic life, the salvage value at disposal, and the interest charged on investment. The anticipated economic life of 5-10 years for industrial robots may be somewhat shorter for construction robots operating under rugged environment conditions.

- set up costs - include the installation of the equipment at its work place, the running in, learning and programming expenses. The construction robot will operate from different work stations, and therefore its setup costs will be composed mainly by the learning expenses of the operators.

- maintenance costs - which include the regular upkeep, the inspection, and the repairs of breakdowns. For reasons explained before, these costs are expected to be higher in construction than in manufacturing.

- operation costs - the electricity consumed for robotic work, and (in construction), the transfer cost of robots from one work place to another.

- indirect expenses - which involve the adaptation of work process to robots employment

and the benefits:

- labor savings, and thereby wages, fringe benefits and other expenses of labor replaced by robots.

- higher quality of product, reflected in material savings (due to higher precision), and better performance of the finished product.

- eliminating or reducing human involvement in hazardous and strainful tasks performed in hostile and harsh environment, and associated with injuries, lower productivity and work stoppages.

3 Investment in Construction Robots

A reliable estimate of investment in a construction robot may be obtained only after the design of development which was discussed in [26], and involved these steps:

- analysis of an activity (or activities) to be robotized, and restructuring it the most adaptible way to robotization.

- defining several alternatives of robot employment with varying degrees of human involvement in the production process.

- selection or preliminary design of components - manipulator, effector, feeding system, control unit, sensors and mobile carriage, for each alternative. The design of the carriage and the manipulator must be sturdy enough to operate in the rugged building environment. On the other hand, for interior robots an excessive weight may entail additional investment in structure. The use of lightweight materials (aluminum, plastics) for the main parts and providing intermediate support to the robot's arm at its maximum reach, may alleviate the weight problem. The sensors should be adapted to interacting with special fixtures rigged into the structure, and the effectors with their feeding system - to performance of specific construction tasks.

- designing a detailed man - robot operation procedure for each alternative.Such design must include adaptation of some building components for easier handling and interaction with sensors, as explained in [26].

- cost estimating of each alternative and selection of the most attractive one.

A general idea of the cost of the *general purpose robot* for interior operations (described in [26]) may be obtained through examining the cost of manufacturing robots of a similar configuration, which have a somewhat shorter reach (2.50m) but a higher payload, than required for construction. It appears that their basic price, including the control unit is usually below $90,000. The additional features in the *general pupose* robot will certainly require an extra investment, however following some preliminary estimates probably not in excess of 50% of the basic price.

The two types of the surface *finishing robots* (horizontal and exterior) do not employ a jointed manipulator and therefore their configuration is much simpler and their cost conceivably lower.

The structure of the *assembling* robot is not different from that of a regular construction equipment - an excavator or a crane. The feasibility study concerns therefore the benefit of its additional (robotized) activities versus the extra investment in effector, control unit and possibly sensors. This investment is very small when compared to the basic equipment cost.

4 Value Estimating of Construction Robots

As was pointed out earlier, it is difficult to examine economic feasibility of equipment which has yet to be developed and processes which have to be restructured for its optimal utilization. The feasibility analysis must be therefore mainly concerned with the value of the construction robot to user.The value of construction robot is defined as the highest price the user may be willing to pay for it while still retaining economic advantage from its use. It will be calculated here as the present worth of the direct savings realized from robot employment less the associated expenses. The additional indirect benefits will be examined in other sections.

The following parameters were used in the evaluation:

a. *economic life* of the robot was assumed 3-5 years. The higher number is normally used as a lower (or most conservative) estimate for industrial robots. The lower number -3 years reflects accelerated wear under the rugged conditions of the construction site. The salvage value at the end of both periods was assumed negligible.

b. *the real interest rate* was assumed as 7-10%. This corresponds to a market rate of 13-16% - normal to high for investment loans.

c. *the maintenance expenses* were estimated as $10,000 per year - roughly a day per month of manufacturer's repair work - including labor and materials. This assumption takes into account the high wear of equipment under construction work.

d. *the operating expenses* - for electric power were estimated, based on information supplied by manufacturers as $1 per hour of operation, or $1,500 per year of use.

e. *the transfer cost* of a robot between two different floor levels (or far removed locations) was estimated as $50 (1 hour of 2 workers involved in this work). Assuming one transfer every 2 days the total cost amounted to $5,000 per year.

f. *the development costs* were not considered here for reasons explained already in Section 2. These costs are either reflected in price, or if funded by public sponsors - offset by the general economic gains.

g. *installation costs* were also neglected. Unlike in manufacturing, where a robot's installation may temporarily immobilize production line, in construction the robot can be employed - in the beginning - within a framework of conventional construction with other tools used in the process. The necessary learning of robot use will become with the acceptance of robotization a standard part of the general construction training.

h. *amount of labor saved*, can be estimated with satisfactory reliability only after a detailed design of the robotized process. Various studies of robots employment in manufacturing cite replacement ratio of 1 robot per 1.3-1.5 workers ([15]). There is every reason to believe that this ratio in construction, in well structured tasks, will be higher than in manufacturing considering the present lower extent of mechanization, poorer work organization, worse working conditions and greater physical effort, all of which create a higher potential for improvement. In the following analysis, the whole range of labor saving between 1 and 2 workers (or 1,500-3,000 hours per year) per robot, was examined.

i. *the cost of labor saved* per hour was estimated to include the following components (based on [12]):

- wages (including fringe benefits) which in 1983 averaged \$18.70 for the various trades of skilled workers in the whole of the United States. The rate varied within a range of ± 13% from this average, for the various trades, and within a range of ± 30% for the various localities in the U.S.

- worker's compensation insurance which in 1983 averaged 9% of the wages for all trades in the whole of U.S. The insurance varied between 20-27% (for construction steel workers and painters) and 5% of the wages (for pipefitters and cement finishers). The average varied considerably between various states.

- other tax and insurance (U.S. and State Unemployment, Social Security, Builder's Risk and Public Liability) averaging 13.3% of the wages.

- tools and other equipment used on site - 1% of the wages.

- labor related overhead including field supervision, main office and field office expenses - 15% of the wages. Only 30% of this labor-related overhead (i.e. 4.5% of the wages) was included in labor savings as evaluated below..

The wages and the additional expenses enumerated above amounted on the average (for all of the US) to \$24 per hour[2]. The total annual saving for *one* replaced worker, assuming 1,500 working hours per year, was therefore estimated as \$36,000.

j. *The savings due to higher work quality* were not quantified and will be discussed separately in Section 9. It was assumed that they are offset by the various indirect costs of robotization which were also not estimated at this stage.

k. *tax deduction due to depreciation*; with depreciation allowance being a tax deductible expense, it effectively increases the net income of the user. At the tax rate of 50%, the annual income is effectively increased by 10% of the investment for robot service life of 5 years, and by 16% for robot service life of 3 years.

The value of robot may be calculated therefore from the following equation as the net worth of service:

$$P = (k\ L - M - O - T + rP)\ \frac{(1+i)^n - 1}{i(1+i)^n}$$

[2]For some localities they amounted to \$31 per hour.

with:

L - the saved labor cost per year per one replaced worker
k - the number of replaced workers
M - the cost of robot's maintenance per year
O - the cost of robot's operation per year
T - the cost of robot's transfers per year
r - the deduction rate (10-16%)
i - the interest rate (7-10%)
n - the economic life cycle of a robot (3-5 years)

The values of a robot to user calculated under different assumptions of economic life, labor saved and interest rate, are presented in Table 2.

Table 1: Robot value to user under different assumptions

Labor Saved	Robot value to user ($)			
	n = 3 years		n = 5 years	
	i = 10%	i = 7%	i = 10%	i = 7%
k=1 worker	80,925	88,220	119,202	135,508
k=1.5 workers	155,625	169,655	229,234	260,593
k=2 workers	230,325	251,090	339,266	385,678

It appears from table 6.1 that the value of the robot varies between $81,000 (for k = 1, n = 3 and i = 10%), and $386,000 (for k = 2, n = 5 and i = 7%).

The value is particularly sensitive to changes in economic life cycle, and the number of workers replaced. It is less sensitive with respect to the interest rate.

5 The cost of construction hazards

Construction is apparently one of the more hazardous industries in the U.S. economy. Compared with manufacturing it has seven times as many fatalities per worker and twice as many disability injuries [11]. The major causes of construction accidents are falls of workers from scaffolds and roofs, falls of materials, accidents involving cranes and materials handling, and collapse of excavations and tunneling.

The total economic impact of accidents in construction in the U.S. - direct and indirect - is estimated in [18] as $8.9 billion per year. The direct part of this cost is born by the construction industry through workers compensation payments for insurance which covers medical and hospital care, compensation for lost income or disability, rehabilitation costs, and in the case of death-payments to dependents and burial expenses. The insurance payments which average 9% of the wages depend on the type of the occupation. The payments for some of the more hazardous trades are given below(from [12]):

Painters, structural steel	27.5%
Pile drivers	17.2%
Rodmen	15.2%
Roofers	16.3%
Structural steel workers	19.2%
Welders - structural steel	19.2%

It may be seen that most of these trades are associated with roofing or structural steel. There are also differences in insurance payments between various locations. The average for all trades varies between 5% of wages at some locations, and 30% - at others.

The indirect accidents costs involve the loss of productivity, disrupted schedules, administrative time lost for investigation and reports, wages paid to injured and other workers for time not worked, clean up and repair work, equipment damage etc. It is estimated in [18] that these indirect costs are 4-17 times higher than the direct accident costs.

The individual contractor pays for workers compensation insurance premium which may increase by 50% and more with respect to the average, if the incidence of accidents in his company is significant. He bears of course all the indirect expenses involved with the accident. It may be assumed that the replacement of labor by robots especially in the more hazardous tasks, will decrease the incidence of accidents, and thereby both the direct and the indirect costs involved.

Assuming that the average direct safety costs are approximately represented by the workers compensation insurance payments, it may be concluded that utilization of robots for more hazardous tasks may result in savings amounting to about 20% of the labor cost. The savings in indirect expenses, as explained before, will be many times higher.

6 Loss of Productivity Under Harsh Climates

Most construction work is carried out outdoors, and its productivity is therefore very much affected by the prevailing weather conditions.

Various studies indicate productivity dependence on the ambient temperature and relative humidity. An optimal productivity of electrical workers in construction, examined in [13] was achieved at a relative humidity of 20-60% and a temperature between 40°F and 70°F. At *effective* temperatures of 30°F - 0°F, the productivity declined by 2 % - 23%, respectively. (The *effective* temperature, with regard to human performance, depends on the prevailing wind velocity. Winds at 10-20 MPH lower the effective temperature, with reference to actual readings, by 15°-30°F, respectively.) The productivity at temperatures of 90°F - 110°F declined by 6% - 40%, respectively. Work at effective temperatures below -10°F and above 110°F had to be stopped altogether, and even at more moderate levels, required special rest and adjustment periods.

A study described in [10], showed a decline of more than 40% in bricklayers productivity, with reference to an optimum at 75°F (and relative humidity of 60%) when the temperature dropped below 35°F or increased beyond 95°F.

Both studies indicated an even higher drop in productivity when the relative humidity was higher than 60%.

Other studies [20], [27] present similar results with respect to productivity losses at very low or very high ambient temperatures.

Table 6.1 shows the number of days per year, in selected states, when the temperature exceeds 90°F or drops below 32°,F over the whole working day. It appears from this table, that in many areas of the U.S. as much as 20% - 30% of the time the labor productivity is considerably affected by weather conditions. Part of this time, under very cold weather, the work stops altogether.

A reliable estimate of the total loss of productivity in construction work due to harsh ambient conditions requires a thorough analysis of the meteorological data - temperature, humidity, precipitation and wind velocity and its changes throughout the year and the working day, in the various geographical regions. However it maybe safely assumed, based on studies outlined above that in the time of excessive weather conditions indicated in Table 6.2, the productivity of many building trades drops by at least 20% - 30%, under temperatures exceeding 90°F or falling below 32°F.

Another very important economic aspect of harsh weather conditions is its effect

Table 2: Periods of harsh weather in selected states (based on data collected in representative locations)

State	Days of max. temp. below 32°F	Days of temp. exceeding 90°F	Total no. of harsh weather days
Maine	76	5	81
New Hampshire	51	11	62
Vermont	76	5	81
Michigan	57	10	67
Wisconsin	65	11	76
Minnesota	100	14	114
North Dakota	101	14	115
Montana	48	18	66
Pennsylvania	27	16	43
Florida	-	100	100
Alabama	-	81	81
Mississippi	-	80	80
Louisiana	-	67	67
Texas	1	83	84
New Mexico	6	61	67
Arizona	13	100	113

Source: Ruffner and Bair, "The Weather Almanac", 1977

on the building schedule. The schedule may be affected either directly, by work stoppage due to very cold weather, precipitation or strong winds, or indirectly - by lower productivity of critical building trades.

The main economic implications of the extended construction duration are two:

a. idleness of indirect and fixed contractor's resources - such as managerial and clerical personnel, facilities, and the site equipment, whose purpose is to direct, monitor and assist the direct labor engaged in construction. The cost of these resources amounts to about 20% [12] of the direct labor cost. An extension of one month in the construction process entails therefore an economic loss which amounts to 20% of the direct labor monthly cost, under full employment.

b. loss to owner due to extended construction time. The loss can be calculated in two ways: *either* as the foregone revenue from the operation of completed building during the extension period, *or*, as the interest which could be received elsewhere from the resources invested in building, during the extension period.

Following this second and more conservative assessment method of owner's economic loss, let us assume that the total owner's investment in project is P; and that it accumulates linearly over the construction time (i.e. owner's payments are evenly divided over the construction time). His *average* investment P_A over the total project construction time will be:

$$P_A = \frac{P}{2} \tag{2}$$

assuming also that the extension of project duration is ΔT, and the interest on investment i, the economic sacrifice will amount to:

$$\Delta C = \frac{P}{2} \Delta T \, i \tag{3}$$

with a real rate of interest of i = 10% per year. The delay of 1 month in the project duration incurs therefore additional cost to the owner which amounts roughly to about 0.4% of his total investment in the project.

The economic impact of these costs can be combined both from the point of view of the contractor and that of the owner. Additional contractor's cost due to delay, will be reflected in his price to the owner. Additional owner's costs due to delays may be reflected in contractor's penalty (or their preventions in an extra bonus) depending on the contract provisions between the two parties. In any case the economic effect of the delays may be combined from the point of view of both sides.

The combined impact of the delays may be illustrated in a case of a project which under satisfactory weather conditions could be completed within 1 year, and in a region of harsh weather will suffer a delay of 2 months due to work stoppages and reduced productivity of construction labor.

The contractor's loss in terms of fixed resources amounts to 20% of the labor cost in those 2 months, or to about 3% of the total labor cost in the project. This is equivalent (assumung that the cost of labor is 25% of the total project cost) to 0.8% of the total project cost. The owner's loss also amounts (from eq. 3) to 0.8% of the total project cost. The combined loss totals therefore about 6% of the labor cost or about 1.5% of the project cost.

In view of these considerations it is clear that employment of robots for performance of human tasks (at least in shell assembling operations) under harsh weather conditions may have very positive influence on the productivity in construction.

7 Effects of Overtime Work

Evidence [17] [20] shows that extended periods of overtime work affect adversely productivity and may also contribute to an increased rate of accidents. The cost of overtime to the contractor increases both due to reduced labor productivity and a higher rate paid for overtime work. These two effects and their combined influence on the average cost of labor are illustrated in Table 6.3, for an overtime payrate amounting to 150% of the regular 40 hours rate.

Table 3: The Effect of Overtime on Labor Cost

Hours per Week	Overtime Work Weeks	Actual Productive Hours	Production Efficiency	Effective cost per hour* (% of reg. rate)
40	0	40	100%	100%
	0-2	46.3	93%	119%
	2-4	45.0	90%	122%
50	4-6	43.5	87%	126%
	6-8	40.0	80%	137%
	8 and up	37.5	75%	147%
	0-2	54.0	90%	130%
	2-4	51.6	86%	136%
60	4-6	48.0	80%	146%
	6-8	42.6	71%	164%
	8 and up	39.6	66%	177%

* Average cost per hour assuming overtime pay rate of 150% of regular rate.
Source: "Scheduled Overtime Effect on Construction Projects", A Construction Industry Cost Effectiveness Task Force Report.

It is evident from Table 3 that overtime work, especially over extended periods of time, may lower productivity and increase effective labor costs, in some cases by 50% and more. According to [19], about 20% of all construction projects apply overtime on a regular basis, most of them to shorten construction time or to make up for slippages of schedule. It is to be expected that employment of robots, whose productivity is not affected by overtime or shifts work, may yield considerable economic gains under such circumstances.

8 Other Effects

In addition to the various factors discussed above, there are many others which increase the cost of work by their adverse, direct or indirect, effect on performance of human tasks in construction.

The ability to perform physical work is markedly reduced at high altitudes, especially if the work is done by workers not accustomed to this type of environment. It is estimated (in [20]) that the productivity of work performed at elevations of 10,000 feet may be reduced by 20-30%. Employment of robots in such locations may bring again considerable economic savings.

There is not as yet quantitative data about the effect on labor productivity of other environmental factors associated with construction work. It is known, however, (as explained in [28]) that noise, vibrations, poor illumination, inconvenient work posture, may have both short and long term effects on workers' health and performance. Another source of potential health hazards to workers (according to [7]) is their exposure to various chemical elements in construction materials. Thus, exposure to cement, concrete admixtures, form oils, mineral and glass wool insulation, asphalt, caulking and sealant materials, adhesives, paints, plasters, drywall materials, may cause skin, respiratory tract, lungs and eye irritation and thus have both immediate effects on labor productivity and also long term effects on their health.

It was noted before that as yet there is no sufficient information to assess in economic terms the effect of these factors on the long term labor performance, or the incidence of possible health damages. It is quite certain, however, that replacement of humans by robots in tasks with a high exposure to these physical and chemical hazards must have long range positive economic consequences.

9 The Benefits of Quality

The benefits of a higher quality of building components due to robotization could be the following:

- material savings due to lower tolerances and better control of robotized operation.
- less repairs work, due to poor workmanship during the construction process. Such work involves cracks, blemishes, dimension mistakes etc.
- less maintenance expenses and longer economic life of building components.

- higher user satisfaction with better performance of the buiding. Usually more evident is user's dissatisfaction with various consequences of poor quality such as moisture penetration, peeling of paint, visible cracks etc.

Although the economic implications of these benefits seem to be self evident it is in most cases very difficult to obtain data for their quantitative assessment. The material savings during the construction are perhaps the easiest to evaluate (a posteriori), if a construction company keeps strict records of its material allocations to the various activities in systems with different degrees of process industrialization. This author's studies revealed that in activities such as spraying or concreting a higher accuracy and a better quality control could have saved in many cases up to 5 - 10% of the materials costs. The savings in repair work on site ,attained with a higher level of industrialization can be also established by a systematic follow up in different projects as in the case of materials use.

The long range implications of quality with regard to building maintenance costs are much more difficult to establish and require keeping well structured records over long periods of time in projects performed under similar conditions with different technologies. It is however estimated in various sources that the annual maintenance expenses of a building amount to 0.6 - 1.0% of its initial cost, and the savings here may be quite significant.

The value of a higher user satisfaction should be theoretically assessed through his willingness to pay more in order to avoid the various inconveniences and even hazards, associated with inferior quality. Since it is almost impossible for a user to perceive in specific terms the potential hardships due to lower quality, except in very well defined cases it would be also impossible to assign it a quantitative price tag.

A Delphi study cited in [15], based on opinions of experts and robots users in manufacturing , estimated the value of a higher quality of product in a robotized process as at least 50% of the value of their productivity gains. There is every reason to believe that a building construction which has less precise working tools and a less stringent quality control than manufacturing industries can derive even larger benefits from process robotization.

10 Economic Implications

It was estimated in section 4 that the value of a construction robot to user, under normal working conditions, may vary between $81,000 and $386,000, depending mainly on the economic service life of the robot and the amount of labor saved by its employment.

It was already mentioned that the lower limit of the expected economic life of manufacturing robots is 5 years. This is also the lower limit of economic life expectation for most types of major construction equipment. There is, therefore, no reason why a construction robot cannot be designed at the development stage, with respect to its motors, carriage and manipulator as well as an appropriate maintenance procedure, for a life span of 5 years. There is always a possibility that the rate of technological innovation will make such robots obsolete over a shorter period of time; this will happen however, only if they will be replaced by others with a still higher value to user, i.e., making the automation process even more attractive.

Assuming an average productivity of a robot to be higher by 50% than that of a worker (at least in certain construction tasks),the value under normal conditions, of a construction robot to user - with a 5-year lifespan, will be $229,000 - $261,000 (for interest rates of i = 10% and 7%, respectively).

It was shown in Sections 4 - 7 that for certain types of hazardous activities, work performed under harsh weather conditions, in high attitudes or over periods of extended overtime the productivity of robots (with respect to humans) may be much higher than under normal conditions, and consequently their value to users will also be greater. The increase in value is shown in Table 6.4.

It may be seen from Table 4 that under conditions described in 5 - 6 where the productivity of labor considerably declines with respect to the normal, the value of robot-to-user may increase by as much as 40-60%.

Finally, the value of robots will be higher when replacing better than average paid trades or at locations with higher than average labor costs. The effect will be similar to that obtained when replacing workers with lower productivity, as shown on Table 4.

To determine the feasibility of the robots employment, the value should be compared with the cost of the construction robots which was discussed in Section 3

Table 4: The Change of Robot Value Under Declining Labor Productivity			
Decline in labor productivity* (%)	Robot value to user ($)** i = 7%	i = 10%	Increase in value (%)
0	261,000	229,000	--
10	298,000	262,000	14%
20	336,000	295,000	29%
30	373,000	328,000	43%
40	411,000	361,000	57%

* With reference to normal conditions which assume 1.5:1 robot to worker ratio.

** Assuming 1,500 employment hours per year, and 5 years economic service life.

.The value of a robot to user (as assessed here), when compared with the basic cost of similar manufacturing robot leaves a margin of over 150% for additional features required in a *general purpose* construction robot. The margin for the *two finishing robots* or the *assembling robot* is probably even larger.

Based on the above estimates it seems, that at the present stage of technological development, robotization has a very good chance of economic viability, when applied to well adapted construction works , given careful design, good maintenance procedures, and an adequate work volume.

It should be remembered on the other hand that the feasibility of robots will be ensured only if they will be employed under proper circumstances. The most important factor in this respect is the intensity of their employment, measured in the number of working hours per year.

If for 1,500 hours of employment, under normal conditions as defined before, the value of robot to user is $229,000 - $261,000 (for interest rates of 10% and 7% respectively), its value for an employment of 1,000 hours per year, (with maintenance and operating expenses declining proportionately), will be only $153,000 - $174,000.

For 500 hours of employment the value will decline to merely $76,000 - $87,000 which will most probably make robotization unfeasible.

Additional important factors are the robot operation and maintenance costs. The costs will depend on the efficiency of maintenance and the project configuration affecting the frequency of robot transfers during the operation.

Each increase in operating and maintenance expenses by $1,000 per year will lower the value of robot to user by an additional $6,100 - $6,900 (for interest rates of 10% and 7% respectively).

By doubling the number of transfers between floors or distant locations from 100 to 200 per year, the value of robot will decline by $30,000-$35,000.

The final feasibility range with respect to utilization rate, labor replacement factor and configuration of the building to be constructed can be determined after implementation design as outlined in Section 3.

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