The repetition effect in building and construction works

A literature review

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Preface

This report summarises the results from the work undertaken for the Public Transport Authority on the effect of learning and repetition in building and construction works.

The project was carried out in May and June 2009 by the Danish Building Research Institute, Aalborg University in close dialogue with the Public Transport Authority.

The authors wish to extend their warn thanks to Steen Lichtenberg, Lichtenberg & Partners, and Svein Bjørberg from Norwegian Multiconsult for their insightful comments to earlier versions of this report.

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August 2009

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Content

1. Introduction

Background

The Public Transport Authority (Trafikstyrelsen) in Denmark has been assigned the task by the Danish Parliament to investigate the opportunities for establishing a new railway between Copenhagen and Ringsted. Two options are being investigated: 1) Extending the existing railway link over Roskilde with a fifth track. 2) Establishing a new railway link over Køge.

The Ministry of Transport and Energy, which includes the Public Transport Authority, has introduced a new budgeting model. In comparison with previous practice, the new budgeting model introduces two new supplementary instruments. These two instruments are:

- The use of evidence-based adjustment factors.
- The use of external project reviews.

As part of the new budgeting model, the Public Transport Authority has asked SBi to conduct a study on the effect of repetition of construction works in order to provide the basis for establishing adjustment factors relevant to the establishment of a new railway link over Køge.

Scope and purpose

The purpose of the study is to:

- Review the experiences and lessons learned on the repetition effect in building and construction works.
- To report on the findings to the Public Transport Authority in Denmark in order to ensure proper documentation.

The scope of this study is restricted in a number of important ways:

- First, the study has been undertaken during a period of 2 months.
- Second, the review of experiences and lessons learned is predominantly based on a literature review, and not on practical experiences.
- Third, the authors of this review only have a very superfluous impression of the additional analyses conducted by the Public Transport Authority and how this particular review will sit with these other analyses.
- Fourth, if possible the study will focus on earth work and construction of bridges, whereas the procurement of e.g. steel/iron for the rail is not included.

2. Research design

The study applies the following methods:

- A literature review of the Danish and international literature on the repetition effect on building and construction works.
- An expert consultation by email correspondence and personal meetings where the assumptions, analyses and conclusions will be validated by other experts.
- Participation by the project group in the debates between the Public Transport Authority and the Danish Construction Association (Dansk Byggeri) on the most adequate procurement methods to exploit the repetition effect.

The structure of the literature review

The following review protocol specifies the methods that will be used in the review.

Search strategy

The basis for the literature review is a survey of the past 10 years' issues of the core construction management journals encouraged by CIB – the International Council for Research and Innovation in Building and Construction along with and the predominantly UK based journals on quantity surveying. These journals include:

- Construction Management and Economics.
- Building Research and Information.
- The International Journal of Construction Management.
- Australian Journal of Construction Economics and Buildings.
- Engineering, Construction and Architectural Management.
- The international journal of Construction Procurement.
- RICS Research Paper Series.
- ASCE *(*American Society of Civil Engineers)

In this first step a complete list of all indexed articles, papers and reports have been compiled using the RefWorks tool. Abstracts have then been processed and relevant articles containing empirical data on effects of repetition were identified to further use in the study.

The second step involved has been to 'roll the snowball'. Through the reference lists of the articles identified in the first step and drawing on our international network most notably CIB we have further identified relevant studies, articles and researchers on the subject.

The third step has been to extend the search for literature through the international construction literature database ICONDA.

In the fourth step we extended our search even further to other literature databases to account for further documentation. We have conducted searches in the following databases:

- Digital Article Database Service – DADS.
- BYG-ERFA.
- Byggedata.
- CSA/ASCE Civil Engineering Abstracts.
- CSA Engineering Research Database.
- ICONDA.

- Web of Science.
- ARCOM.

In a fifth step, we expanded our search even further to include various websites containing information on cost etc. on civil engineering works, most notably roads. These sites included among others the construction cost database of the World Bank and the International Union of Railways.

Review selection criteria

In Denmark the term 'repetition effect' has circulated in governmental and research spheres since the 1960s. It has since evolved into a sort of 'umbrella term' covering a variety of different concepts that either builds on the notion that it in one way or another is possible to improve productivity (whether on a project, firm or sectoral level) by capitalising on economies of scale. This can e.g. be in the form of 'volume economies of scale' or 'learning economies of scale.' The first is created as increases in production capacity cause lower unit costs, whereas the latter, learning economies of scale, is created as technical knowledge gained through company experience permits various changes to be made that lead to better and more efficient use of existing resources (Pearson and Wisner, 1993: 13). Pearson and Wisner (1993: 14) illustrate this accordingly:

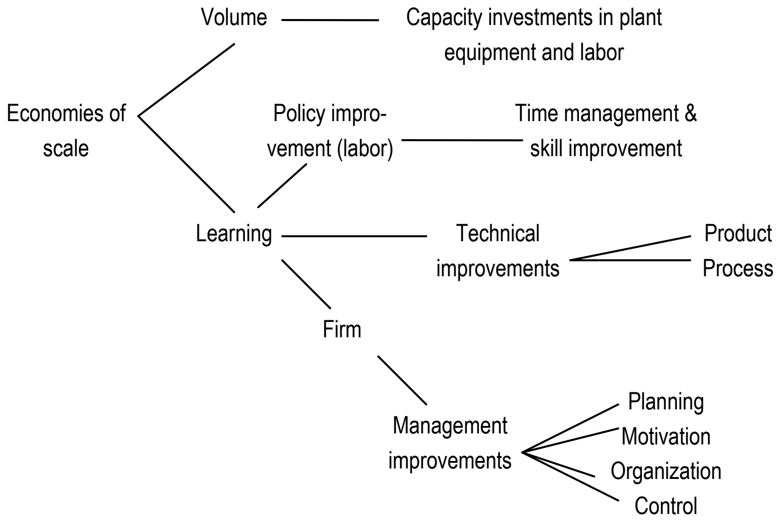


Figure 1. Comparison of volume and learning economies of scale (Pearson and Wisner, 1993: 14).

To this a third type of 'instrument' in the cost reduction efforts can be added – that of buying power. We have used the above distinction between learning and volume economies of scale and buying power in the literature review to group the various types of 'repetition effects' we encounter in the international literature.

Data extraction

This chapter presents the results from a systematic theoretical review (Cooper, 1989; Kitchenham, 2004). The aim is to demonstrate how the academic literature treats the notion of effects of repetition in construction. The review was undertaken searching peer-reviewed journals in a variety of different database as given above. As point of entry for the review, we started by searching explicitly for documents containing the phrase 'effect of repetition'. The reason for choice of this particular starting point was to find documents referring the 1965 report from the United Nations' Economic Commission for

Europe entitled 'Effect of repetition on building operations and processes on site' as this is widely regarded to be the first and hitherto most elaborate scientific attempt to explore factors relating to the effect of repetition in the building and construction industry.

Using the UN report as the starting point, we accessed the articles citing the report in order to compile the controlled and uncontrolled terms as well as the descriptors associated with these citing articles in the different databases.

Table 1. Results from the literature search.

Search string	No. hits	Related terms	Recurrent authors
KW="effect of repetition"	3	learning effect	
KW="economies of scale" DE=construction	50	learning effect/curve	
KW="learning effect"	119	learning	Thomas
KW=productivity AND KW=improvement AND KW=learning	84	learning curve	
DE=construction, KW=learning AND KW=curve* and	62	construction costs	Thomas, Farghal, Everett, Couto
DE="construction costs"	16,842	N/A	-
DE="construction costs" AND learning	240	N/A	-
DE="construction costs" AND saving*	996	productivity	-
DE="construction costs" AND saving* AND learning	9	learning curves	Couto
DE="construction costs" AND saving* AND reduc*	411	N/A	-
DE="construction costs" AND saving* AND reduc* AND repe*	2	learning curves	Thomas

In a number of iterations, this eventually lead to a revised search for using the descriptor 'construction' together with the two uncontrolled terms 'learning' and 'curve*'. This preliminary search yielded a total of 62 articles, and after cleaning the lists for double counting, editorials, book reviews and articles containing the word 'construction' used in a different meaning than to refer to the construction sector we ended with 27 articles dealing with the subject. Of these 27 article, a total of 11 had 'construction cost' as descriptor, which we used as point of entry in approaching the notion of 'effects of repetition' from another angle to validate the results from the first search; however without new documents showing up. In the next chapter we will discuss the findings from the literature review.

3. Defining the concept

As previously argued, the 1965 report from the United Nations' Economic Commission for Europe entitled 'Effect of repetition on building operations and processes on site' is widely regarded to be the first and hitherto most elaborate scientific attempt to explore factors relating to the effect of repetition in the building and construction industry. Below we use this report as the entry point in the attempt to define the concept of effects repetition in building and construction works.

Historicising effects of repetition in building and construction

A first attempt to quantify the effect of repetition in building was made in an enquiry undertaken between 1960 and 1962 by the United Nations' Economic Commission for Europe (Economic Commission for Europe, 1963). This first study dealt exclusively with the relationship between the size of series and unit costs in the manufacturing of building materials and components. In 1965 another report by the United Nations' Economic Commission for Europe (1965) ended the second stage of the Commission's work on the effect of repetition on building construction costs (Ibid., 1965: i). This report was devoted to the study of the effect of repetition on building operations and processes on site.

The 1965 report consists of a collection of evidence of the effect of repetition emerging partly from national studies in twelve countries already published and partly from other relevant material submitted by the governments. The twelve countries, which contributed to the study, were: Bulgaria, Czechoslovakia, Finland, France, the Federal Republic of Germany, Hungary, the Netherlands, Norway, Poland, Sweden, the Ukrainian SSR and the United Kingdom.

The scope of the 1965 study was restricted to the following primary aspects of the problem of repetition (Economic Commission for Europe, 1965: 3):

- The effect of repetition on the cost and productivity of building operations on site.
- The effect of repetition on operational times.

On the effect of repetition on building costs, the following *causa* is given:

> *'The economic effect of repetition of on site operations is due to a decrease in operational costs, on the one hand, and to indirect cost savings caused by the reduction of construction time (lower labour on-costs, costs for finance, machinery and equipment, etc.), on the other. The direct savings in operational costs depend, in turn, on the gradual decrease in operational time attained in repetitive work, on better organization and greater specialization of the work, as well as on the higher degree of mechanization which may be justified in serial production.' (Economic Commission for Europe, 1965: 13).*

On the effect of repetition on operational times, the following is written:

> *'The favourable influence of repetition on operational time is due to increased labour productivity achieved by training but also by successive improvements of work method and arrangements in the immediate environment of the actual operation, as well as a steadily improved attun-*

> *ing within the gang and between the gangs engaged on the operation.' (Economic Commission for Europe, 1965: 8).*

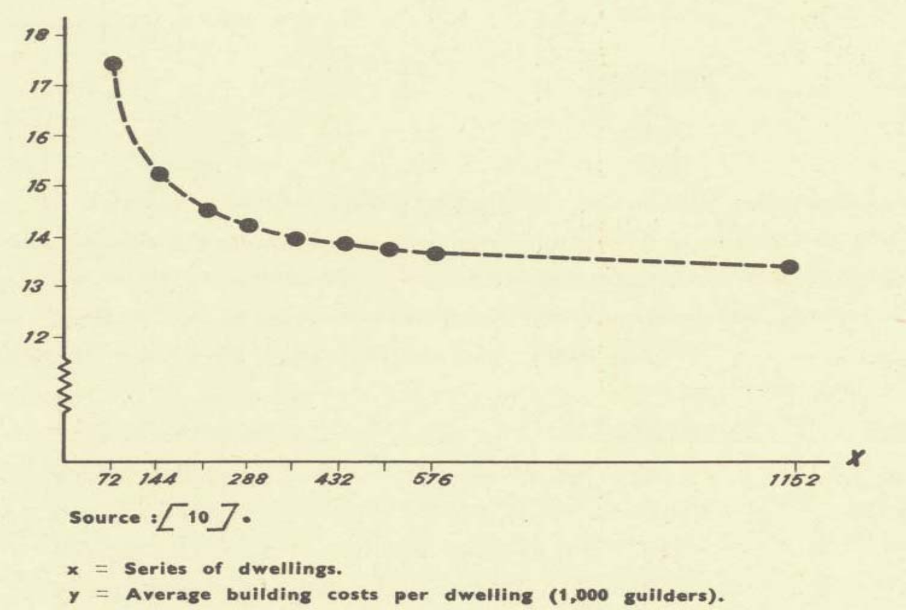
Below we discuss the theoretical implications of these aspects of the problem of repetition.

The effect of repetition

The report concludes that one of the most important factors influencing direct as well as indirect building costs is the type of remuneration system. This factor, however, entails the following dilemma:

> *'If a purely hourly wage system is employed, the entire economic gain from improved efficiency will appear in terms of lower wage cost. On the other hand, as the earnings will not reflect the results of the work, the operatives will have no great inducement to improve their ability.' (Economic Commission for Europe, 1965: 13).*

As for the piece-rate system, which is the common remuneration system in Denmark, the advantages and disadvantages are the reverse of the above. Based on experiences from the Netherlands, it is concluded that a clear effect of repetition on labour consumption will be achieved *only* when a wage system is applied that offers the required incentives (Economic Commission for Europe, 1965: 85). Under these circumstances the effect of repetition on building costs is however also documented:



Source : [10].

x = Series of dwellings.
y = Average building costs per dwelling (1,000 guilders).

Figure 2. Average building costs per dwelling in the serial production of identical dwellings (Economic Commission for Europe, 1965: 90).

These findings correspond somewhat to those documented by Gottlieb et al. (2003) who, based on numbers from the Danish National Agency for Enterprise and Construction (EBST), have documented a contemporary correlation between project size (number of dwellings per project) and the total square meter cost.

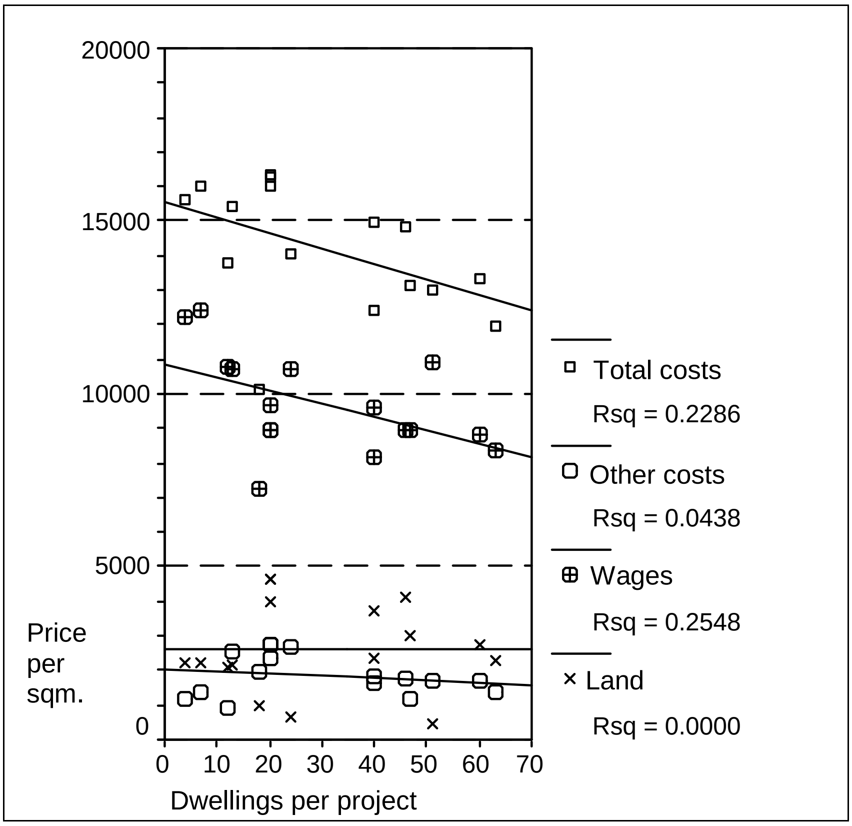


Figure 3. Costs per square meter housing (Gottlieb *et al.*, 2003: 12).

Although not specifically dealing with identical dwellings, the figure illustrates the assumption, that there is a statistical significance between number of units completed and the average building cost. Appendix A contains a calculation with the learning effect for social housing projects in Denmark.

Similar tendencies are documented by the World Bank (Estache and Iimi, 2008: 28), who attribute the following curve effects of economies of scale:

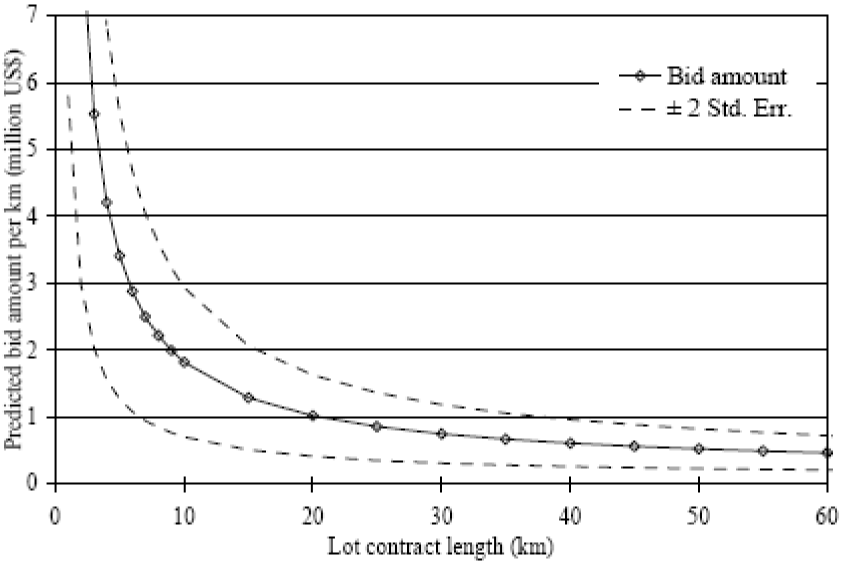


Figure 4. Predicted Road Unit Bid by Lot Length (Estache and Iimi, 2008: 28).

Estache and Iimi (2002: 27; own emphasis) write:

> *'In addition, the predicted unit cost is significantly affected by contract design, especially the size of contract. When the estimated equilibrium bid function for road projects is evaluated with different lengths of roads, it is evident that a road of less than 10 km would be extremely expensive […] Hence, how to design lot packages is an important issue. As expected, large electricity projects have a lower unit cost, because of economies of scale.'*

Thus, whether attributed to economies of scale, there seem to be a relationship between unit costs and number of units produced.

Returning to the 1965 UN report, it is documented that in the most countries contributing to the study, the following principal phases of improvement can be distinguished:

Table 2. Principal phases of improvement (Economic Commission for Europe, 1965: 21).

Principal phase	Explanation
The operation-learning phase	The period during which the worker acquires sufficient 'know-how' of the task to be performed.
The routine-acquiring phase	The period during which successive improvements of performance are achieved through growing familiarity with the job and through small changes in work method and organisation.

The operation-learning phase can be further subdivided accordingly:

Table 3. Sub-phases of the operation-learning phase (Economic Commission for Europe, 1965: 21).

Sub-phases of operation-learning	Explanation
The initial organisation of work	This phase may take some time depending on the knowledge of the job manager.
The real operation-learning phase	The period during which the workers are being taught how to carry out the new job.

The improvement of operational times achieved by repetition during the phases described is usually illustrated by means of what is called improvement, learning or experience curves.

These curves show the decrease in resources (typically man-hours or costs) and the number of operations completed. The typical hypothetical learning curve shows a classical concave shape (Thomas, 2009: 15):

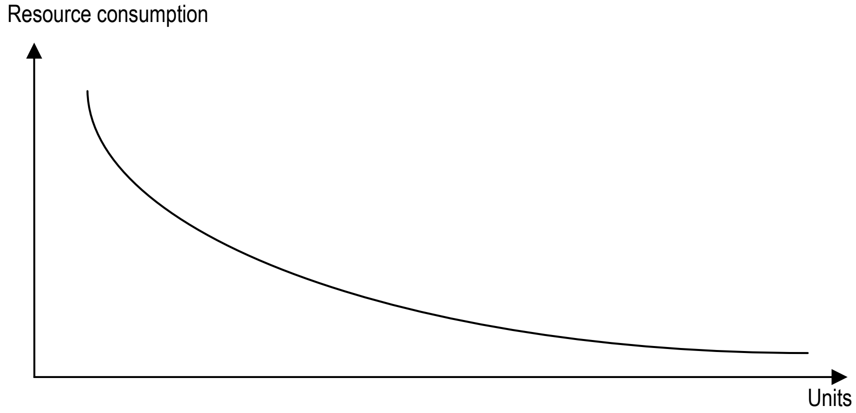


Figure 5. Hypothetical learning curve showing a classical concave shape (adapted after Thomas, 2009: 15).

The above hypothetical learning curve is of the general shape of '*…improvement curves reported by different experts*' (Economic Commission for Europe, 1965: 22) found in the 1965 UN study. The general hypothetical learning curve displays a classical concave shape, which can be constructed by means of a logarithmic regression function of the form $y = ax^b$.

4. Learning curves geometries

The above logarithmic regression function ($y = ax^b$) for the effects of repetition on operational times was imported to the construction sector in the 1960s from the manufacturing industries, where it for a long time had been subject of attention and study.

Wright's power formula

One of the best known studies on the effect of repetition on operational times in the manufacturing industries was published by Wright (1936) in his study on the factors affecting the cost of airplanes. Wright (1936) studied the accumulated mean values of operational times accordingly (Economic Commission for Europe, 1965: 23-26):

If the times per unit are denoted $T_1, T_2, T_3, \ldots, T_x$, then the accumulated mean value t_x for the first x units will be:

$$t_x = \frac{T_1 + T_2 + T_3 ... + T_x}{x}$$

Wright found that a logarithmic regression function of the form $y = ax^b$ can be used as t_x can be represented as a function of t_1 and x_1:

$$t_x = t_1 x^{-k} = \frac{t_1}{x^k}$$

In this formula $-k$ is a parameter characterizing the improvement (or the 'elasticity' of the improvement). Wright determined b (k) as 0.322, and the equality $2^{-0.322} = 0.80$ results in Wright's 80 % rule saying that the accumulated mean value of operational time will be reduced to 80 % when doubling the number of identical operations.

Accordingly the function for the individual value of operational times per unit (T_x) can be expressed as follows:

$T_x \approx (1-k)T_1 x^{-k}$, where T_1 is the operational time for the first unit.

The general formula for calculation of the progress rate (k) for the logarithmic function is:

$k = -\frac{\log(1-\Phi)}{\log(2)}$, where Φ is the reduction in per unit cost/time/etc. per doubling in cumulative production output. Thus, an 80 % learning rate (equalling a 20 % reduction as per Wright's rule) can be written as follows, giving rise to the aforementioned 0.322 value:

$$k = -\frac{\log(1-0.2)}{\log(2)} = 0.322$$

Evidence from the building (housing) industries in Finland, Sweden and Denmark from the 1960s and 1970s (Boestad and Göransson, 1962; Gabrielsen, 1963; Arctander and Christiansen, 1966; Lyngsøe-Petersen, 1967; Pedersen, 1973) show that the equivalent of Wright's 80 % rule in building operations of a repetitive nature is 87 to 93 %. This carries the implication that effects of repetition in the building and construction industry generally speaking is lower than in the manufacturing industries.

Other learning curve geometries

Although Wright's model for learning curves is the most commonly used, many other geometric versions of the learning curves exist. Yelle (1979) lists the following models:

1. The log-linear model.
2. The plateau model.
3. The Stanford-B model.
4. The DeJong model.
5. The S-model.

These five models are illustrated below:

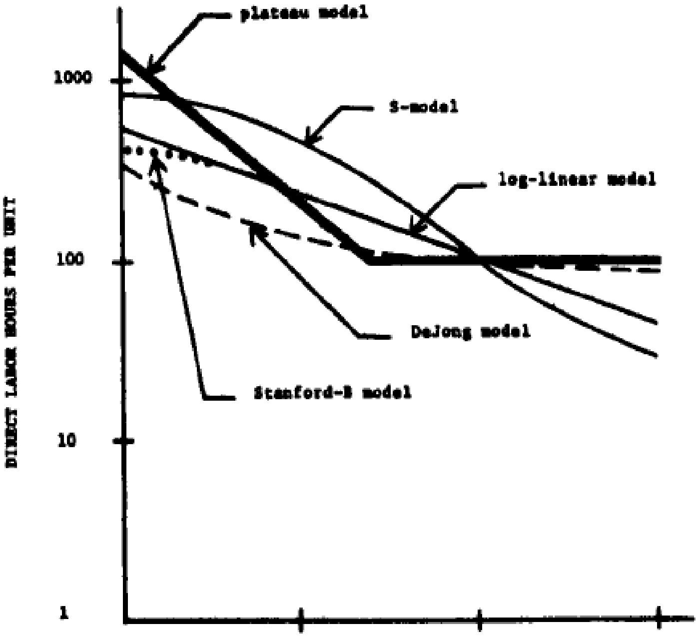


Figure 6. Various Learning Curve Models All Having the Same Value of *y* at I00 Units (Yelle, 1979: 304).

According to Yelle (1979) the reason for the search for something other than Wright's log-linear model stems from the fact that the log-linear model does not always provide the best fit in all situations.

The Stanford-B model is a modification of the basic linear-log model that includes a so-called B-factor:

$$y = a(x + B)^b$$

Whereas the Wright formula establishes the function for the accumulated mean value, the Stanford-B model establishes the function for the individual value of operational times per unit. Here *y* is the worker-hours required for cumulative unit number *x*; *a* is a constant, equivalent to the worker-hours of the first unit when a crew has no prior experience; *b* is the learning index describing slope of the asymptote; and *B* is a constant, equivalent to units of experience available at the commencement of an activity, or equivalent to the number of units produced prior to the first unit acceptance. The value of B will be in the range of 0-10 (Kara and Kayis, 2005: 209).

The DeJong model can be seen as an improvement of Wright's linear-log model based on the assumption that there in a specific work operation are a varying number of elements, for which the time consumptions cannot be reduced. Thus is expressed with a so-called factor of incompressibility (*M*):

$$y = a\left[M + \frac{1-M}{x^b}\right]$$

M assumes a value in the range of 0-1, where *M* = 0 represents a complete manual operation, and *M* = 1 describes a completely automatic operation.

Using the notation from the Wright example above, the DeJong formula can also be written accordingly (Lichtenberg and Schiøtz, 1973):

$$T_x = T_0 + (T_1 - T_0)x^{-k}$$

Here T_0 is the minimum operational time; i.e. the unit time after such a large number of repetitions that it can be considered to be constant.

Finally, we have the S-curve model, which is of the following form:

$$y = a\left[M + \frac{1-M}{(x+B)^b}\right]$$

The S-curve model is based on the assumption of a *gradual* start up. The S-curve function therefore has the shape of the cumulative normal distribution function for the start-up curve and an operating characteristics function for the learning curve (Kara and Kayis, 2005: 211).

Thus even though the linear-log model has been and still is the by far the most widely used model (Yelle, 1979: 304), Everett and Fargahl (1994) documents with historical data for 60 construction field operations that:

> *'Cubic models in general provide better correlation to historical data that the quadratic models, which are superior to the linear models.' (Everett and Fargahl, 1994: 607).*

Everett and Fargahl (1994: 615) however also note that although:

> *'…various forms of cubic learning curve models generally give the highest correlation to completed repetitive construction activities […] the cubic models are poor predictors of future performance and should not be used to estimate performance beyond known historical data.'*

Further it is stated that:

> *'…the linear log x, log y learning curve model [i.e. the Wright model] is the most reliable predictor of future performance […] cubic models fit the early data best and the linear models fit the later data best. […] In the long run, the best predictor will be a linear learning curve model. Early data can be used to predict the constants in the long-term curve.'*

In their study Lichtenberg and Schiøtz (1973) find that the effect of repetition in Danish construction is best described by use of Wright's model. Below we illustrate these central points through a series of calculated examples on the effect of repetition.

Illustrating the effect of repetition

Using a *k*-value (elasticity of the improvement) of 0.15 in the following, we give some examples on the effect of repetition in building and construction works. The *k*-value of 0.15 is chosen as it according to the equality $2^{-0.15} = 0.90$ results in a 90 % rule, i.e. that the accumulated mean value of operational times will be reduced to 90 % when doubling the number of identical operations. The 90 % is chosen as it corresponds to the mean value of the findings reported in the construction industry (cf. above).

Ideal effects of repetition

Below we have calculated the effects of repetition for a series of identical operations. Consider a situation where a contractor is constructing the overhead contact system as part of a railroad project. Over a distance of 60 km the contractor has to place a total of 1,200 sets of masts (one set of masts per 50 meters) supporting the overhead lines. Assuming that the constant for repetition is 90 % (thus disregarding any factor of incompressibility (*M*), which e.g. the DeJong model takes account for) and that time consumption for the production of the first unit is 50 man-hours, we end up with the following picture:

Table 4. Ideal effects of repetition (Wright's formula).

Total number of units	Total man-hours	Average rate per unit
1	50	50,00
10	354	35,40
20	638	31,90
40	1,150	28,75
80	2,073	25,91
160	3,737	23,35
320	6,735	21,05
640	12,140	18,97
1,200	20,714	17,26

Impact of contract size on effects of repetition

Assuming instead that the overhead contact system contract is divided into two sub-contracts or that two different crews install the masts, we get a different picture.

Table 5. Impact of contract size on effects of repetition.

Contract A. Total number of units	Total man-hours	Average rate per unit	Contract B. Total number of units	Grand total man-hours
1	50	50,00	1	100
10	354	35,40	10	708
20	638	31,90	20	1,276
40	1,150	28,75	40	2,300
80	2,073	25,91	80	4,146
160	3,737	23,35	160	7,473
320	6,735	21,05	320	13,470
600	11,492	19,15	600	22,984

Even though the constant for repetition is maintained at 90 % we clearly observe the consequences of smaller contract in terms of effects of repetition alone. Thus, as can be seen from the below table, when assuming that the experience curve is repeated in each case, two equally sized contracts would cause an additional 2,270 man-hours, corresponding to an 11 % increase. Split three ways, the increase in man-hours would correspond to app. 19 %. *These figures include only the direct effects of repetition and thus ignore costs of mobilising additional crews and equipment.*

DeJong's correction

As can be seen from the above numbers, the Wright formula greatly (over-) values the effect of repetition in that it assumes that:

$$y = ax^b \to 0 \text{ for } x \to \infty$$

As described above, the DeJong model to some extent avoids this by introducing a factor of incompressibility (*M*) representing a number of elements in a specific work operation for which the time consumptions cannot be reduced. Following the above ideal example of the effects of repetition using the DeJong model:

$$y = a\left[M + \frac{1-M}{x^b}\right]$$, we can construct the following figures:

Table 6. Ideal effects of repetition (DeJong's formula).

Total number of units	Average rate per unit	Total man-hours	Average rate per unit	Total man-hours	Average rate per unit	Total man-hours
	M=0		*M=0.5*		*M=1*	
1	50,00	50	50,00	50	50	50
10	35,40	354	42,70	427	50	500
20	31,90	638	40,95	819	50	1,000
40	28,75	1,150	39,38	1,575	50	2,000
80	25,91	2,073	37,96	3,036	50	4,000
160	23,35	3,737	36,68	5,868	50	8,000
320	21,05	6,735	35,52	11,368	50	16,000
640	18,97	12,140	34,48	22,070	50	32,000
1,200	17,26	20,714	33,63	40,357	50	60,000

For *M = 0* (representing fully manual work) the DeJong model show the same results as the Wright model. For *M = 1* (representing fully automated work) effects of repetition are unattainable. For *M = 0.5* (representing manual work dependent on e.g. the capacity of a crane) we see a less drastic reduction in time consumption even though we still operate with an elasticity of improvement of 0.15 (corresponding to an 85 % learning rate).

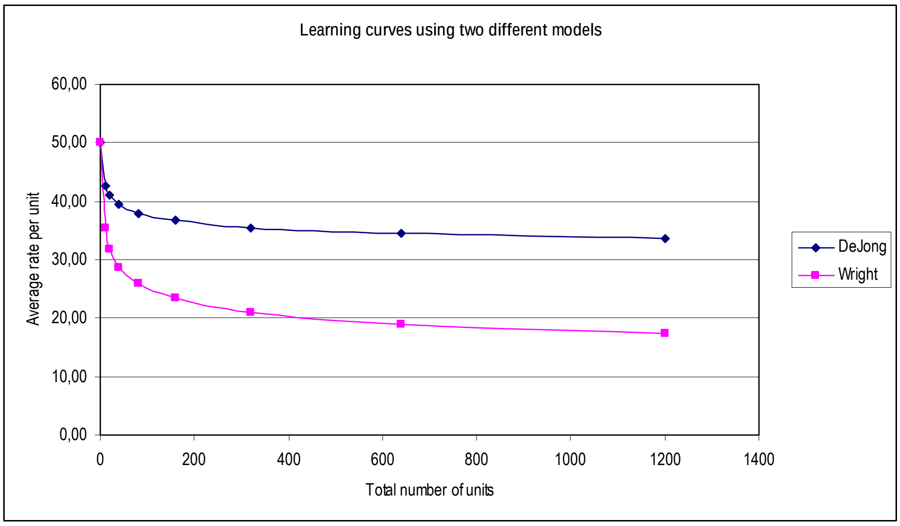


Figure 7. Learning curves (Wright, DeJong (*M = 0.5*).

As can be seen, a 90 % rule can be interpreted differently depending on the constraint placed on the possibilities of harnessing effects of repetition.

Further modifying the Wright, respectively DeJong model, are the Stanford-B and S-Curve models of which the S-Curve model is the most refined, as it operates with both a factor of incompressibility (*M*) and an experience factor (*B*) making the S-Curve model of effects of repetition the most 'conservative' in terms of absolute reductions in average rates per unit from the first to the nth unit.

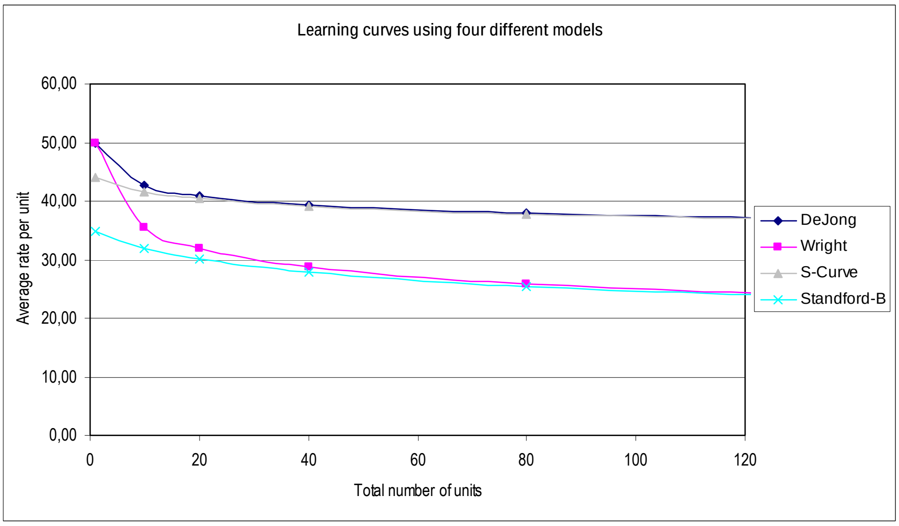


Figure 8. Learning curves (DeJong (*M = 0.5*))(Stanford-B (B = 10))(S-Curve(B = 5), (M = 0.5)).

In the above chart we have plotted the learning curves using the constants *M = 0.5* and *B = 5* for the S-curve and *B = 10* for the Stanford-B curve to illustrate these models in relation to the corresponding DeJong and Wright models. As argued by Everett and Fargahl (1994) we clearly see that it is the early data that generates the differences between the four models when focusing on the average rates per units.

Table 7. Ideal effects of repetition (S-Curve (B = 5, M = 0.5) formula).

Total number of units	Total man-hours	Average rate per unit
1	44	44,11
10	417	41,65
20	809	40,43
40	1,565	39,12
80	3,027	37,84
160	5,860	36,62
320	11,360	35,50
640	22,063	34,47
1,200	40,351	33,63

Comparing the above S-Curve data with the corresponding DeJong dataset, this becomes especially evident as the relative difference between the dataset is reduced from 11.78 % to 1.28 % in a little more than four doublings.

Table 8. Model difference – the impact of the early dataset (S-Curve (B = 5, M = 0.5) formula).

Units	S-Curve	Stanford-B	Relative difference (%)
1	44,11	50,00	11,78
10	41,65	42,70	2,45
20	40,43	40,95	1,28
40	39,12	39,38	0,64
80	37,84	37,96	0,31
160	36,62	36,68	0,15
320	35,50	35,52	0,07
640	34,47	34,48	0,03
1,200	33,63	33,63	0,02

In the next chapter, we will take a closer look at these idealized effects of repetition.

5. Discussion

In this chapter we discuss the different learning curve geometries and their underlying assumptions *vis-à-vis* experience data from the international literature.

Summary of the literature review

Table 9 below contains a list of the studies of learning curves and the effect of repetition in building and construction works identified in the review.

Table 9. Article summary matrix.

Authors	Type of study	Segment	Learning curve model	Estimate of benefit	Proxy for learning effect	Facilitators (+) Inhibitors (÷)
Arditi, D., Tokdemir, O. B., & Suh, K. (2002).	Conceptual, modeling	Linear projects	Linear (non-logarithmic)	Line-of-Balance Scheduling supports learning	Time/duration	Activity interdependencies, Nonlinear and discrete activities (÷)
Birrell, G. S. (1980).	Conceptual	Construction	N/A	N/A	?	-
Chau, K. W., Poon, S. W., Wang, Y. S., & Lu, L. L. (2005).	Quantitative analysis	Sector	None	None	Size/time	Degree of subcontracting (÷)
Chiang, Y., Tang, B., & Wong, F. K. W. (2008).	Survey, quantitative analysis	Public housing	Economies of scale, bargaining power, networking	None	Volume of work	-
Couto, J. P., & Teixeira, J. C. (2005).	Case, numerical analysis	Housing	Wright	85 % learning rate	Time/cost/manhours	Discontinuities (÷)
Everett, J. G., & Farghal, S. (1994).	Conceptual, quantitative analysis	Construction	Multiple	Wright model is most reliable fit for future performance	Activities/units, time	Complexity (+)
Everett, J. G., & Farghal, S. H. (1997).	Conceptual, quantitative analysis	Construction	Multiple	Unit data outperform cumulative average data in predicting future performance	Activities/units	-
Farghal, S. H., & Everett, J. G. (1997).	Conceptual	Construction	Multiple	Future performance can be predicted accurately at 25 - 30 % of activity completed	Activities/units	-
Gates, M., & Scarpa, A. (1972).	Conceptual	Construction	N/A	N/A	-	-
Hassanein, A., &	Conceptual	Highway con-	None	Resource-driven	Units	Relocation, ob-

Moselhi, O. (2004).		struction		scheduling ensures crew work continuity, which maximizes the benefit of the learning curve		structions (÷)
Hijazi, A. M., AbouRizk, S. M., & Halpin, D. W. (1992).	Conceptual, numerical analysis	Construction	Wright, DeJong, Stanford B, Cubic	80 - 95 % learning rate	Units/time	Work complexity (+)
Kara. S., & Kayis, B. (2005).	Conceptual, quantitative analysis	Housing	Wright, DeJong, Basic exponential, S-curve	Wright-model as most reliable predictor for future performance	Number of iterations	-
Kumaraswamy, M., & Dulaimi, M. (2001).	Case	Sector	None	None	-	-
Lee, E. P., Lee, H., & Ibbs, C. W. P. (2007).	Case	Highway construction	None (fast-tracking, accelerated construction)	17 - 43 % increase in production rate	Time	Interruptions (÷)
Lee, E., Lee, H., & Harvey, J. T. (2006).	Case	Highway construction	None (fast-tracking, accelerated construction)	10 - 43 % increase in production rate	Time	Interruptions (÷)
Link, H. (2006).	Case, econometric analysis	Highway construction	N/A	N/A	Quantities of labour, material and capital	-
Linton, J. D. (2002).	Conceptual, forecasting	Construction	New product growth model	N/A	Time	-
Liu, W., Flood, I., & Issa, R. R. A. (2005)	Conceptual	Continuous linear projects			-	-
Lutz, J. D., Halpin, D. W., & Wilson, J. R. (1994).	Numerical analysis, simulation	Construction	Wright	68 - 100 % learning rate	Quantities	-
Moselhi, O., & Hassanein, A. (2003).	Conceptual	Linear projects	None	N/A	Time	Obstructions (÷)
Nembhard, D. A., & Uzumeri, M. V. (2000).	Conceptual	Individual learning	Wright, DeJong, Stanford B, S-curve, Cubic, a.o.	Best fit discussion	Work	-
Paulson, B. C. J. (1975).	Conceptual	Construction	-	-	-	-
Sander, T. C. P., & Roesler, J. R. P. (2006).	Case	Infrastructure	-	-	-	-
Thomas, H. R. (2009).	Conceptual, quantitative analysis	Construction	Experience data	Unit data outperform cumulative average data in predicting future performance	Practice	Uniformity in measurements, repetitious layouts, table work environment (+)
Thomas, H. R., Mathews, C. T.,	Quantitative analysis	Construction	Wright, Stanford B, Cubic, Piece-	82 – 99 % learning rate	Units	*I.a.* stabilized design (+)

& Ward, J. G. (1986).			wise Exponential			
Walsh, K. D. (2007).	Conceptual, numerical analysis	Construction	Linear (non-logarithmic)	N/A	Time	Continuity (+)
Wong, P. S. P. (2007).	Case, conceptual	Construction	Wright, Two-parameter hyperbolic, Three-parameter hyperbolic, Two-parameter exponential, Two-parameter exponential	Three-parameter hyperbolic model provides highest prediction accuracy	Units	-

We start by discussing the size of the effect of repetition in building and construction works. From here we proceed to scrutinize the learning curve in general. In doing so we highlight in more details some general results and lesson learned from specific cases identified above and we discuss the conditions necessary to achieve benefits of repetition. Finally, we summarise the finding by addressing the various empirical findings on the factors influencing the possibilities of benefitting from effects of repetition/learning.

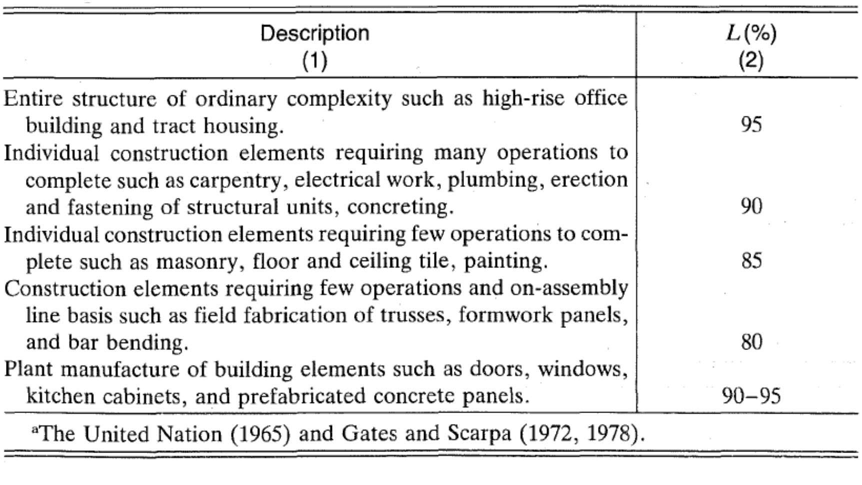
Quantifying the effect of repetition

Not surprisingly, the literature review does not reveal any exact, quantification of the size of the effect of repetition in building and construction works. It is not surprising in the sense that the effect seems highly dependent on the type of work carried out, and the conditions under which the work is carried out. What the study on the other hand does document is that an effect of repetition indeed does exist, and that it is not simply a theoretical abstraction or idealisation.

The study also document that the reported learning rates differ substantially from dataset to dataset, and that anything from 68 to 100 % learning rate (corresponding 0 to 32 % reduction of the accumulated mean value of operational time when doubling the number of operations) can be accomplished.

This is a rather imprecise estimate, and certainly an indication of the absence of a universal/general size of the effect of repetition. Hijazi et al. (1992) attempt to make up for this, by proposing differentiated learning rates for different distinct construction processes as shown above.

Table 10. Proposed learning rates for selected construction processes. *L* is the learning rate (Hijazi et al., 1992: 686).



Description (1)	L (%) (2)
Entire structure of ordinary complexity such as high-rise office building and tract housing.	95
Individual construction elements requiring many operations to complete such as carpentry, electrical work, plumbing, erection and fastening of structural units, concreting.	90
Individual construction elements requiring few operations to complete such as masonry, floor and ceiling tile, painting.	85
Construction elements requiring few operations and on-assembly line basis such as field fabrication of trusses, formwork panels, and bar bending.	80
Plant manufacture of building elements such as doors, windows, kitchen cabinets, and prefabricated concrete panels.	90–95

[a]The United Nation (1965) and Gates and Scarpa (1972, 1978).

As can be seen, Hijazi et al. (1992) have been especially influenced in their efforts by the 1965 UN report treated in a previous chapter. Lichtenberg and Schiøtz (1973) and Schøitz (1970) have taken a similar approach. Their analyses of the effect of repetition were based on 1,000 data sets comprising app. 50 different work operations on app. 20 building sites. The work operation covered mainly concrete assembly, formwork assembly, concrete casting and reinforcement work; however also data on earthwork and sewage work were included. The data thus comprise a varied and representative part of building and construction works in general.

The studies concluded that the effect of repetition was best approximated with the Wright model, and that the effect of repetition *per se* in this study can be defined only by the *k*-factor.

Applying a non-linear regression analysis, Lichtenberg and Schiøtz found that most of their data exhibit a satisfactory fit to the Wright model with *k*-values in the interval app. 0.1 to 0.4, with a mean value of *k* on 0.25 meaning that the accumulated mean value of operational time will be reduced to 84 % when doubling the number of identical operations. As such, the effect of repetition is reportedly higher than that reported by the UN in their pan European study from 1965 (Economic Commission for Europe, 1965). An illustration of this is shown below.

As also can be seen from the below figure, the effect of repetition differs according to the general type of work conducted. As a general rule of thumb it is shown that the more exceptional, complex or unusual a given work operation is, the higher the benefits of repetition.

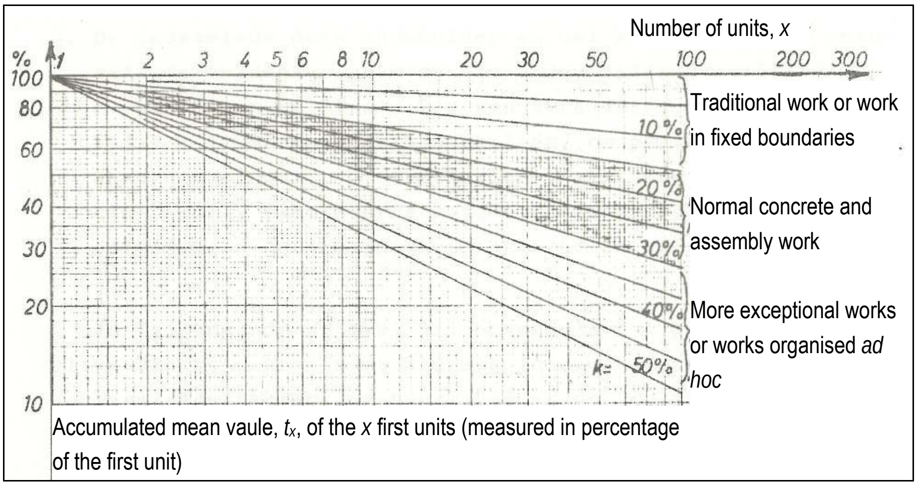


Figure 9. Differing effects of repetition (Lichtenberg and Schiøtz, 1973; own translation)

In summary, Lichtenberg and Schiøtz (1973: 11-12) concluded that:

1. A considerable effect of repetition can be observed in the data material. The effect of repetition seems more prevalent in Denmark than abroad.
2. Production increases occur under normal circumstances throughout the entire duration of the project – by and large proportionally with the logarithm to the conducted workload. This confirms the appropriateness of the Wright model.
3. The collected data contain a number of deviations for the above tendencies that remain unexplained but can be attributed to e.g. errors concerning bookkeeping entries and external influences.

Learning curve theories in Danish agreed documents

As an example of the practical application of the above theories, it can be mentioned that the collective agreements between the Danish Construction Association and the United Federation of Danish Workers contains the following clause on the advance payment for piecework based on time studies

(Danish Construction Association and United Federation of Danish Workers, 2007: 47):

- *If 15 % or less of the number of pieces estimated has been completed, the basic time for the number completed is increased by 40 %.*
- *If more than 15 %, but less than 25 % has been completed, the increase is 30 %.*
- *If more than 25 %, but less than 35 % has been completed, the increase is 25 %.*
- *If more than 35 %, but less than 45 % has been completed, the increase is 20 %.*
- *If more than 45 %, but less than 55 % has been completed, the increase is 15 %.*
- *If more than 55 %, but less than 65 % has been completed, the increase is 10 %.*
- *If more than 65 %, but less than 75 % has been completed, the increase is 5 %.*

The above principle can be illustrated accordingly:

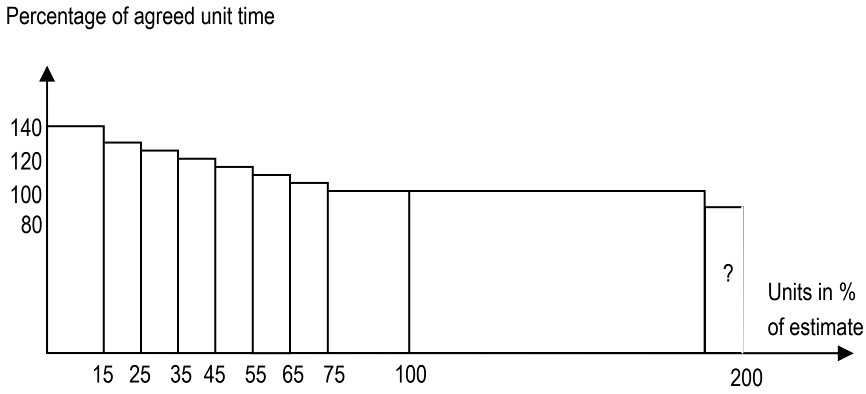


Figure 10. Changes in basic times due to work size change.

Written in the form of Wright's power formula we end up with the below picture, which illustrates a learning curve based on the assumption that the accumulated mean value of operational time will be reduced to 88 % when doubling the number of identical operations – corresponding to a k-value of 0.12.

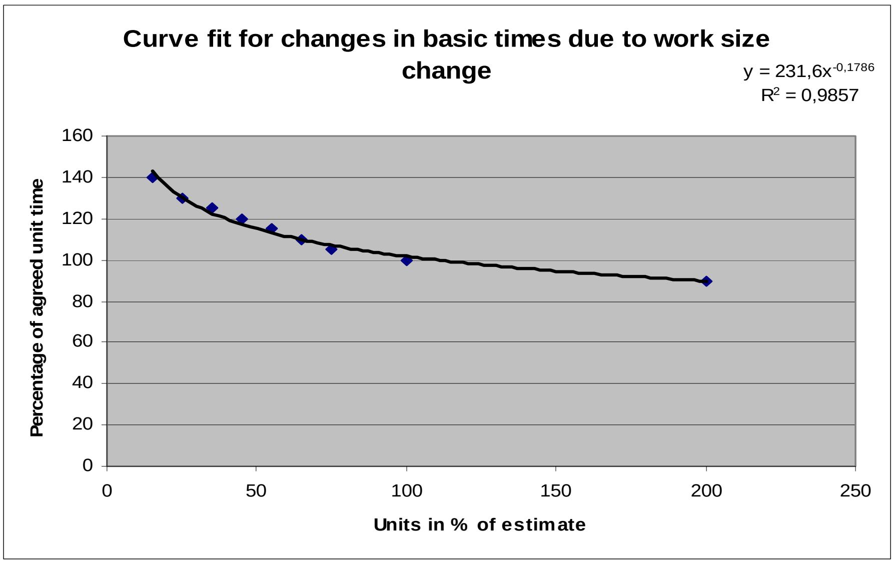


Figure 11. Curve fit for changes in basic times due to work size change.

Furthermore, according to Schwartzkopf (2004: 137) the US Board of Contract Appeals has acknowledged and accepted the use of learning curve theories in calculating and awarding damages to contractors.

Database estimates of the size of repetition

The International Union of Railways (UIC) has collected information from the participating railways for track renewal projects such as renewal of rails, sleepers, ballast or subgrade and combinations of these elements. Based on data from 125 different projects, the UIC has provided project costs (on an inflation adjusted basis) according to the respective project length for different types of project. The illustration below shows the example for combined projects of rail and sleeper replacement. The sample in this case of 34 projects shows a pronounced digression of unit costs per meter of track with increasing project length.

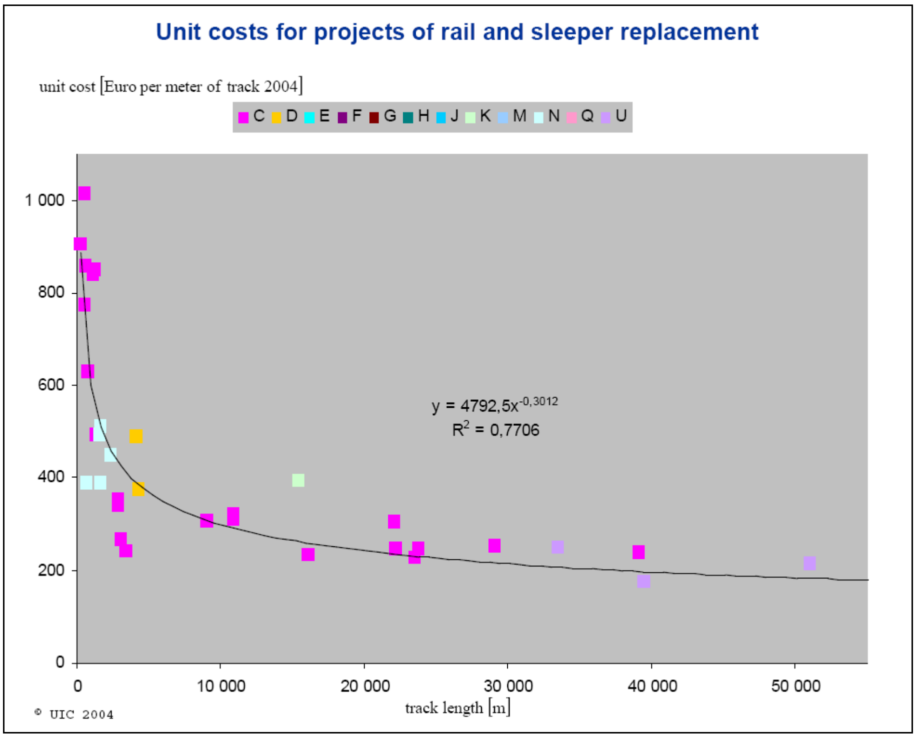


Figure 12. Unit costs for projects of rail and sleeper replacement (UIC, 2006: 9).

As can be seen, the UIC reports an estimated learning rate of 81.1 % with a coefficient of determination on 0.7706. This follows in general, the pattern established previously in the document. For sake of verification, drawing on data from the World Bank, we have in Appendix A provided a series of similar calculations in other types of construction works. These are summarised below.

Table 11. Summary of learning rates.

Case	Size parameter	Learning rate	Coefficient of determination	Range
Construction of new 2L highways in Poland	Length	79.7 % *k* = 0.33	0.34	1 – 31.4 km
Construction of new 4L highways in Poland	Length	90.2 % *k* = 0.15	0.23	1.8 – 15.6 km
Strengthening of roads in Bangladesh	Length	62.0 % *k* = 0.69	0.39	49.6 – 105.6 km

Routine maintenance of 2L highways in Uganda	Length	79.3 % *k* = 0.33	0.46	15,0 -233,0 km
Highway widening projects in Thailand	Length	87.8 % *k* = 0.19	0.14	21.0 – 83.7 km
Heavy metros (global)	Length	108.1 % *k* = -0.11	0.01	14.0 – 43.0 km.
Surface railway lines (global)	Length	91.2 % *k* = 0.13	0.71	8.5 – 66.0 km.
Light rail systems	Length	66.0 % *k* = 0.49	0.50	4.2 – 70.0 km.
Social housing	Sqm.	94.4 % *k* = 0.08	0.20	720 – 12,425 sqm.
Danish Association of contractors	% of agreed work	88 % *k* = 0.18	0.99	0-100 %

As can be seen from the above calculations, the learning rate varies from 62,0 % to 108,1 %; however both of these values should be taken with some degree of caution for two different reasons. First, the range of data for the first value is in the interval of 46,9 to 105,6 meaning that we lack data in the interval from 1 to 46, where the variance normally is most pronounced. Secondly, we have a low coefficient of determination for the latter value, meaning that the result is highly questionable. *For all of the observed datasets we confirm the existence of a 'learning effect' – whether attributable to economies of scale or effects of repetition.* The only exemption is in relation to the least reliable case (heavy metros) where the unit cost increases as a function of the size parameter – indicating diseconomies of scale.

Scrutinizing the learning curve

Even though there seem to be a widespread consensus that it is possible to achieve benefits of repetition, evidence also shows that we need to scrutinise the favoured *Wrightian* hypothetical learning curve more closely if favourable effects of repetition are to be harvested.

The UN (Economic Commission for Europe, 1965) thus states that during the operation-learning period an uninterrupted and continuous decrease is seldom obtained. The routine-acquiring period is described as occurring either as a direct continuation of the operation-learning period or every time a new work is started in a field in which the operator is trained and qualified (Economic Commission for Europe, 1965: 22). Take as example the below illustration:

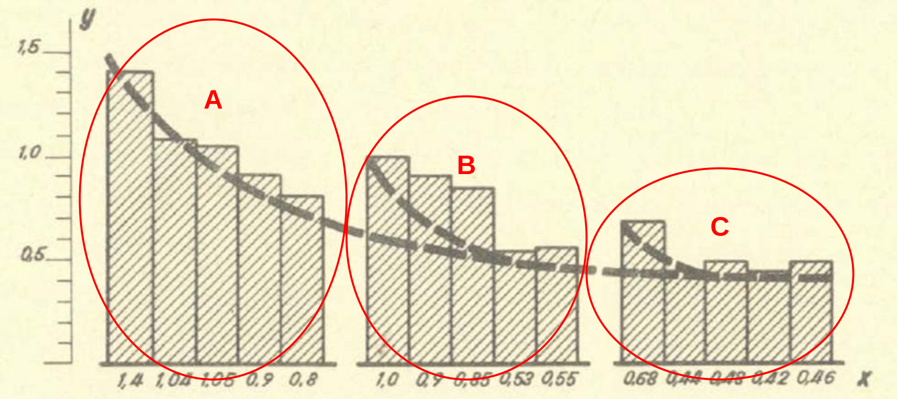


Figure 13. Time consumption in the serial execution of assembling formwork (Economic Commission for Europe, 1965: 34).

Here we see the results of a study of the time consumption in the serial execution of assembling formwork for in situ cast concrete floors. We have here three groups of floors. Each group encompasses formwork conducted on five floors respectively above the basement (A), above the first floor (B), and above the second floor (C). For all 15 operations of assembling formwork, we observe a learning curve corresponding to the hypothetical curve shown in the above Figure 5. More interesting, however; is that we observe local increases in time consumption initially as segments B and C are initiated.

We can in other words argue that a number of conditions exist that have to be handled in order to gain favourable effects of repetition.

Conditions necessary to achieve effects of repetitive work

Once again we refer to the 1965 UN report as the starting point for this discussion. The Economic Commission for Europe (1965: 92) thus argues that

> *"If an improvement in operational time and a decrease in building costs are to be obtained as a result of repetition, certain conditions must prevail. The most important of these conditions is continuity of work. The operations to be carried out must be identical (operational continuity) and they have to be executed by the same operatives and, as far as possible, without breaks (executional continuity)" (Economic Commission for Europe, 1965: 92).*

The fulfilment of these conditions is facilitated by the following parameters:

A. Architectural and structural plans ensuring maximum identity of operation.
B. Adequate size of projects allowing for sufficient specialisation as well as sufficient space for each of the work gangs involved.
C. Proper preplanning and organisation of site works.
D. Adequate day-to-day management and supervision of site works.

Two factors in particular were reported to exert influence on the possibilities of harnessing benefits from effects of repetition on operational times, being: a) complexity; and b) continuity.

We will briefly highlight the most important conclusions pertaining to these factors. Speaking from a very general perspective, the report concluded that the possible improvement in labour productivity as a result of repetition is greater for complicated operations than for simple operations (Economic Commission for Europe, 1965: 35). At the same time, it is however also claimed that the possible degree of improvement achievable by repetition is greater in non-traditional operations than in traditional ones.

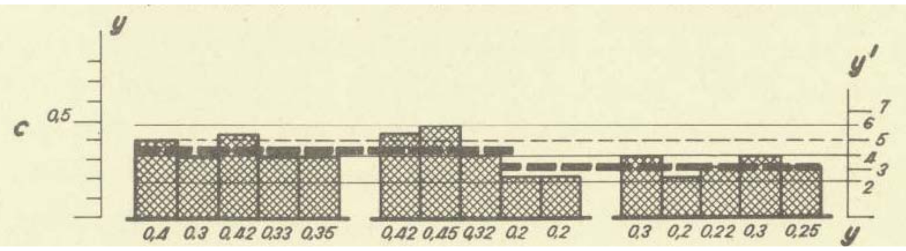


Figure 14. Time consumption in the serial execution of concreting (Economic Commission for Europe, 1965: 34).

As can see seen above, the time consumption in the serial execution of concreting is more or less constant throughout the process. Further, in reporting the findings from a German study, it is documented that concerning building operations such as e.g. bricklaying:

> *'…it was almost impossible to observe any improvement…' (Economic Commission for Europe, 1965: 35).*

Secondly, it was noted that:

> *'…a successive improvement of labour productivity is achieved in all kinds of building operation, carried out consecutively and continuously in series.' (Economic Commission for Europe, 1965: 10).*

Positive effects of repetition are thus reported to be dependent on the continuity of operations in order to be achieved. Time breaks are thus reported to be avoided as interruptions result in a:

> *'…serious decrease in the capacity of the work team' (Economic Commission for Europe, 1965: 99).*

This is illustrated accordingly below with an example taken from the Swedish one-family house building industry:

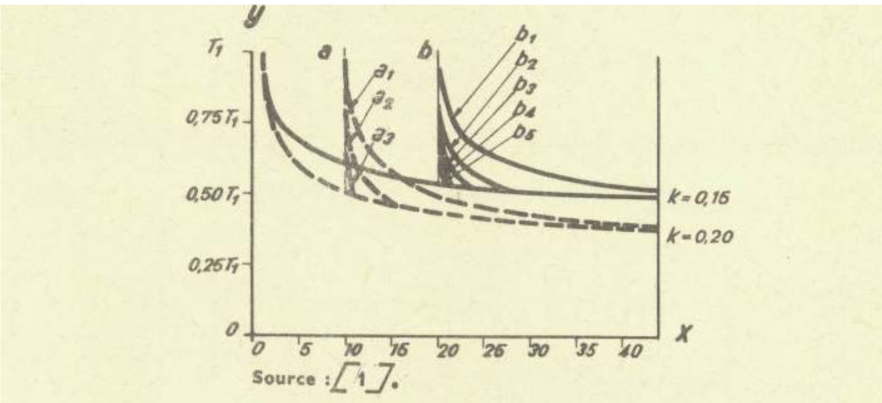


Figure 15. Theoretical analysis of the effect of breaks after the 9th and 19th repetitions of identical operations (Economic Commission for Europe, 1965: 102).

Here we see that time losses due to interruption of work sequences generally is greater the later the break occurs in the production process. This is hardly surprising as all curves depicted fit the general hypothetical learning curve.

Proxies: factors influencing effects of repetition and learning

As can be seen from Table 9, we have identified a series of proxies for the learning/repetition effect being:

- Activities.
- Time/duration.
- Quantities of labour/material/capital.
- Work.
- Practice.
- Size.
- Volume of work.
- Units (unspecified).
- Man-hours.

These elements should be seen as 'proxies' for a learning/repetition effect, with which is meant that they are used in the respective studies as parameters according to which progress is measured. The scope of different proxies used goes to show two things:

1. That it is difficult to isolate a single variable accounting for benefits of repetition or learning.
2. That even though we focus strictly on a single notion ('learning curve') in our literature search and that the found references to large extent cite each other, there is not a single conceptualisation of the phenomenon, which on the contrary seems to embody many (if not all) of the notion we set out to differentiate in figure 1.

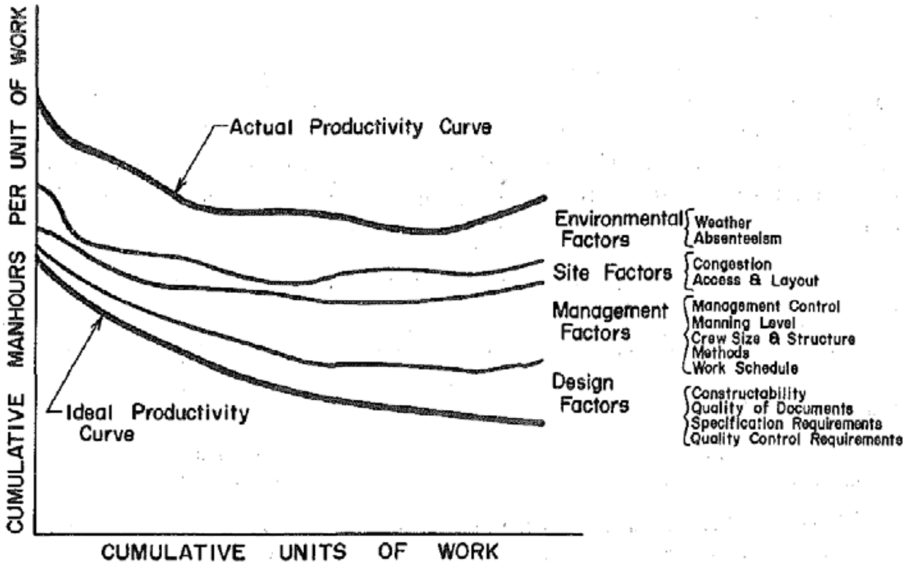


Figure 16. Factor Model of Construction Productivity (Thomas and Yiakoumis, 1987: 627).

As consequence, when focussing strictly on factors influencing effects of learning and repetition from the point of the above proxies, we end up with a rather dispersed image, as the following factor model illustrates.

As can be seen, Thomas and Yiakoumis (1987) have identified a series of factors that can explain deviations from an ideal productivity curve in an actual setting; however based on the previous findings, we can say it is possible to stimulate some factors towards achieving increased effects of repetition.

Schwartzkopf (2004) is even less precise in his assessment of factors effecting productivity. He lists the following partial list of factors:

1 Job familiarization.
2 Equipment and crew coordination.
3 Job organization.
4 Engineering liaison.
5 Day-to-day management and supervision.
6 Development of better construction methods.
7 Sufficient workspace for crews.
8 Development of more efficient material supply systems.
9 Development of better and more efficient tools and equipment.
10 Stabilization and product design.
11 Lot size increase.

As result, in the following we have 'translated' and grouped the above list of proxies and factors into the following meta-factors:

- Complexity.
- Continuity.
- Duration.
- Mechanisation.
- Size/quantities.
- Accessibility.
- (Management – degree of delegation of responsibility).

These have been chosen for their ability to grasp at the most general level the different facets addressed by the various discrete factors. The meta-factors should be understood accordingly:

Complexity

Complexity is identified as a key aspect when discussing the potential for repetition in building and construction works. The more complex a given operation to be performed is, the higher the learning effect from one identical operation to the other is. The argument is that the more complicated an operation (or contract is) the less complete is the information we have concerning its optimal baseline – and the greater the progress from unit to unit is.

Continuity
Continuous work is an enabler of positive effects of repetition. If work is interrupted, we move back the learning curve, and are unable to benefit from the learning gained from the previous identical work.

Duration
As a proxy for learning, project duration seem relevant in assessing the potential for effects of learning and repetition. As the work duration for a single unit comes closer to zero, the higher the inaccuracy of the measurement will becomes, and the smaller the relative learning effect becomes. As an example the relationship between accelerated construction and effects of learning and repetition can be observed. Here we argue that there is a trade-off between the two:

- *Accelerated construction* uses various techniques and technologies to help reduce *construction* time.
- Effect of repetition on *operational* time – is focussing on the micro level from the point of the single operator (e.g. a gang).

Accelerated construction focuses on the grand total, i.e. the macro level, of the time consumption of the project, so the dilemma is – do you want potential cost savings on the project level (due to effects of repetition) – or is more macro-economic models/considerations employed, e.g. that a higher project cost is accepted as it entails fewer nuisances for the society (through accelerated construction).

Mechanisation
Increasing degree of mechanisation is counter-conducive to effects of learning, as 'the pace of the machine' sets the baseline for how long an operation takes.

Size/quantities
Same argument as for duration, only here we can consider the perspective of depreciation of machinery. The cost of expensive machinery has to be depreciated. The larger a given contract is, the lower the marginal contribution of the cost of machinery is. This can be considered here.

Accessibility
Accessibility pertains to factors such as worksite lay-out, access to work, congestion etc. Work e.g. in urban areas and on small and crammed sites, where work is predicated on the terms of existing physical constraints placed on the site is highly countering the possibilities of harvesting positive effects from learning and repetition.

Management – degree of delegation of responsibility
Finally, also a factor such as the degree of delegation of responsibility seems to exert influence on the size of the learning effect. This is a factor that commentators argue partly can explain the relatively higher k-value in Danish construction compared to other countries, such as England, Eastern European states, Germany and even Sweden.

Provisos

In general it has to be noted that apart from findings from the 1960s and 1970s hardly any contemporary evidence exist concerning the size of effects of repetition in building and construction works. Furthermore most of the empirical data found often addresses exclusively building projects, whereas civil engineering projects (including infrastructure project) are yet to be targeted these concerns.

Comments to the learning curve theory

When using learning curves, at least two issues regarding the strict mathematics of the curves must be taken into consideration:

- The importance of first time rather than standard times.
- The cumulative average versus the cumulative unit approach.

Cumulative average versus cumulative unit times

As previously demonstrated there are several distinct formulas or approaches for expressing effects of learning/experience/repetition in construction works. The *Wrightian* log-log relationship calculates the *cumulative average time/cost for each of the n units up to the nth unit.* In double-logarithmic scaling the relationship is expressed as a straight line. This is also the case with the unit approach that calculates the *time/cost of the nth unit.* However there are differences in applying a log-linear cumulative average approach (LL-CA) and a log-linear unit approach (LL-U).

Referring Thomas et al. (1986), Wideman (1994: 348) argues that the traditional Wright-model (LL-CA) is useful:

> *'…in forecasting or comparing similar operations but with significantly different numbers of units involved. It is also useful in analyzing large amounts of data as, for example, the records of a large number of units produced from a precasting yard. This is because the cumulative average curve has considerable power to smooth out the unit data. It can also be deceptive because this power increases as the quantity increases (Thomas 1986).'*

In contrast, the approach is less useful when it comes to examining the exact expectations for individual units or the latest unit such as would be needed in tracking actual progress on a construction site. In this respect, the LL-U approach is more suitable.

Where the time for the nth unit (U_n) can be written accordingly in the LL-CA model:

$$U_n = a\left[x^{(b+1)} - (x-1)^{(b+1)}\right]$$

the time up to the end of the nth unit (T_n) in the LL-U model is of the following expression:

$$T_n = \int_0^n (ax^b)dn$$

Wideman (1994) argues that the results of the two approaches are similar but not identical, and that the differences in results obtained from the two approaches vary from about 7 % for a repetition of five units at 95 % learning ratio, to more than a 100 % for 50 units at a learning ratio of 70 %. It cannot however be argued that one approach is better than another, rather that choices have to be made, as to which method of calculation is applied, depending on the specific objective. In this specific project, the LL-CA approach seems relevant due to its forecasting strength.

6. Quantifications and conclusions

The concluding chapter on the effect of repetition in building and construction works is structured into four main parts:

- *Quantification:* Drawing on the literature review we determine the effect of repetition to be in the range of 6 -12 %, which will be used further in the establishment of an index-factor for use in the budgeting of the project.
- *Factors:* We summarise the factors affecting the possibilities of achieving effects of repetition, which are to be applied systematically for every budget account to establish the learning effect.
- *'DNA-profile' of railway project:* Using the Transport Authorities' main account structure from their 'physical estimate' of units and costs, we assess the possibilities of achieving effects of repetition for each account. In doing so, we propose a potential for the effect of repetition for each account.
- *Calculating budget factors:* We summarise the core conditions necessary to take into consideration in relation to the above findings.
- *Further work:* Finally, we recommend the establishment of a research and development project to help monitor the progress of the construction project and establish suitable benchmarks for the future.

Quantification of the learning effect: From potential to effect

As previously written, the literature review does not reveal any unequivocal and exact quantification of the size of the effect of repetition in building and construction works. This is not surprising in the sense that the effect seems highly dependent on the type of work carried out, and the conditions under which the work is carried out. *What the study on the other hand have documented is that an effect of repetition indeed does exist, and that it is not simply a theoretical abstraction or idealisation.*

In assessing the potential benefits from effects of learning and repetition on the Copenhagen-Ringsted project, we operate with the following learning rates, corresponding to the accumulated mean value of operational time/cost for each doubling of the input variable:

Table 12. Learning rates and k-values.

Assessed potential for effects	Learning rate	*k*-value
Potential ≤ ÷ 0,5	108 %	÷ 0.11
÷ 0,5 < potential ≤ 0	100 %	0
0 < potential ≤ 0,5	94 %	0.08
0,5 < potential ≤ 1	88 %	0.18

We have chosen these figures on basis of the literature review. In doing so, we have made several choices in determining the exact values. First of all we have chosen to operate with four scenarios:

- *Diseconomies of scale:* Not ruling out the possible existence of diseconomies of scale, we operate with a *k*-value of –0.11 for works falling in this category. This estimate is highly insecure.
- *Neutral:* No potential for repetition. The status-quo scenario.
- *Moderate potential:* Based primarily on the dataset from the Ministry of the Interior and Social Affairs. Building social housing projects is a well-established and highly regulated practice showing a learning rate, which

we assess would be characteristic of typical building and construction works with a moderate potential for learning and repetition.
- *High potential:* Highly complex projects or work operations with incomplete information. Number based on the figures relating to the clause on the advance payment for piecework from the Danish Construction Association and United Federation of Danish Workers.

As a general point, we stress that these estimates would be considered conservative in the light of the conducted literature study. And although the Danish *k*-value reportedly usually is higher than corresponding foreign values, we have chosen these lower estimates in order not to discriminate foreign contractors employing different management styles and technologies than their Danish colleagues.

Factors

Below, in the assessment of the potential benefits of repetition, we have chosen to focus on the following meta-factors as explained in the previous chapter:
- Complexity.
- Continuity.
- Mechanisation.
- Size/quantities.
- Duration.
- Accessibility.

We have chosen not to consider the degree of delegation of responsibility (project management), as it is not known in a budgeting situation – although it still can be influenced, e.g. through partnering.

Each of these meta-factors can exert either a positive or negative influence on achieving benefits from repetition. As illustrated in the previous chapter, a wide variety of different proxies and discrete factors can be identified. We have however chosen the above six parameters for two reasons:
- They are generic labels applied to the 'proxies' for the learning effect that were identified in the literature review.
- They are somewhat possible to influence through procurement strategies. Complexity is thus fully designable if we seek to further this factor – we could e.g. favour a general contract involving multiple work operations in expense of an individual trade contract involving only a single type of work operation.

Based on the previous literature review, we point to the following *theoretically ideal* relationship between the six factors and the possibilities of achieving benefits of repetition e.g.:
- High complexity is conducive to learning effects.
- High work/task continuity is conducive to learning effects.
- High degree of mechanisation is detrimental for learning effects.
- Higher quantities are conducive to learning effects.
- The longer the (continuous) project duration the higher the learning effect.

'DNA-profile' of railway project

Using the Public Transport Authority's main account structure from their 'physical estimate' of units and costs, in this chapter we assess the possibilities of achieving effects of repetition for each of the accounts. The below chart contains the project main accounts and their relative sizes.

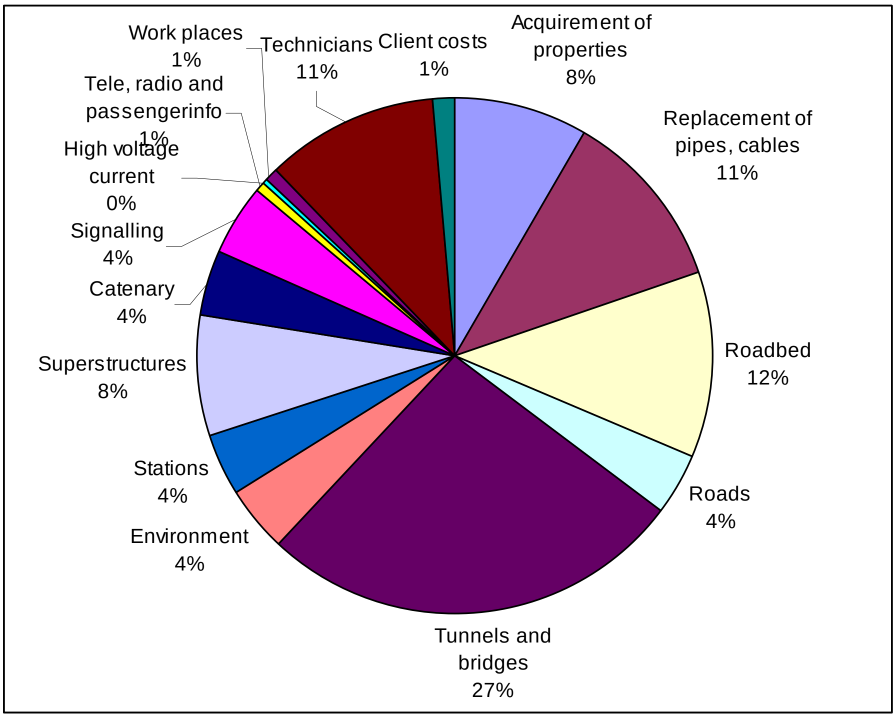


Figure 17. Relative cost distribution on main accounts (Based on data form the Danish Transport Authorities).

In the following we will draw the profile of each main account according to a number of dimensions or factors that can influence either positively or negatively on achieving effects of repetition. In assessing the possible impact from effects of repetition on each factor, we apply a modified three-point Likert scale:

a) (÷1) negative potential impact on repetition.
b) (0) no or insignificant potential impact on repetition.
c) (+1) positive potential impact on repetition.

Table 12. Learning effect assessment matrix. Only examples – estimates to be established by the Public Transport Authority.

Account	Complexity	Continuity	Mechanisation	Quantities	Duration	Accessibility	Potential for learning*
1. Properties	N/A	N/A	N/A	N/A	N/A	N/A	N/A
2. Pipes, cables	+1	÷1	+1	0	0	÷1	0
3. Roadbed	÷1	+1	+1	+1	+1	+1	0.67
4. Roads	0	+1	÷1	+1	+1	+1	0.5
5. Tunnels and bridges	+1	0	0	+1	0	0	0.33
6. Environment	N/A	N/A	N/A	N/A	N/A	N/A	N/A
7. Stations	+1	÷1	+1	0	0	0	0.17
8. Superstructures	÷1	+1	÷1	+1	+1	+1	0.33
9. Catenary	÷1	+1	÷1	+1	+1	+1	0.67
10. Signalling	N/A	N/A	N/A	N/A	N/A	N/A	N/A
11. Tele/radio	N/A	N/A	N/A	N/A	N/A	N/A	N/A
High voltage current	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Work places	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Technicians	N/A	N/A	N/A	N/A	N/A	N/A	N/A
20. Client costs	N/A	N/A	N/A	N/A	N/A	N/A	N/A

Note: * Normalised values.

The above table is only for illustrational purposes. Estimates will need to be established in close cooperation with the Public Transport Authority and their counsellors.

Calculating budget factors

So far we have been approaching the learning effect in relative terms. That is, we have established the constant or the asymptote of the learning curve in a log-log graphical presentation. However, when one wants to make budgets we will need to establish absolute numbers. This in turn requires knowledge of how unit prices have been obtained. Do unit prices in a budget or tender stem from the first unit, the n'th unit or is it an average value effectively smoothing out the learning effect? Clearly, this has great impact on how to calculate the effect in the construction budget. Thus, below we will illustrate that careful attention to the precise definition of unit prices is crucial to make a suitable budget.

Based on the above learning effect assessment method and established k-values, below we present how to calculate the correction factors for use in the budgeting phase. In order to do so, we need first to establish the starting-point for the calculation. Using comparative project data is crucial in this respect. Consider the following situation, where experience data from a completed project ($Project\_{OLD}$) is used as basis for the establishment of the budget for the construction of a similar product ($Project\_{NEW}$).

$Project\_{OLD}$ is the construction of 22 km green field highway and was realised at a total cost of DKK 700 mill. Consider now that an identical type of highway 34 km long is to be constructed. Disregarding possible effects of repetition, we would *ceteris paribus* estimate the cost of the new project at app. DKK 1.082 Million, corresponding to 34/22 times the cost of the old project). However; how can we estimate the cost of the new road using the learning curve theory?

First, the potential for repetition have to be assessed using the *Learning effect assessment method* described above. In the remainder of this example we operate with a *k*-value of 0.08 (equivalent to a learning rate of 94 %). We then have the following input-data:

$$Cost\_{OLD} = 700 mill.$$

$$Unit\_{OLD} = 22 km$$

$$Unit\_{NEW} = 34 km$$

$$k = 0{,}08$$

The adjusted price for the new highway can be calculated accordingly:

$$Cost\_{NEW} = \frac{Cost\_{OLD}}{Unit\_{OLD}} * \left(\frac{Unit\_{OLD}}{Unit\_{NEW}}\right)^{k} * Unit\_{NEW} \Rightarrow$$

$$Cost\_{NEW} = \frac{700 mill}{22 km} * \left(\frac{22 km}{34 km}\right)^{0{,}08} * 34 km = 1045 mill$$

Between the original DKK 1,082 Million estimate (calculated 1:1 on an experience based unit price of DKK 31.8 Million per km. highway for 22 km highway) and the learning curve corrected price we have a factor **0.96** that can be used in the budget phase to account for learning effects.

Likewise, from the learning curve theory, we see that if the new highway were to be completed as two separate contracts, each on 17 km, we get the following subtotal and grand total:

$$Cost_{\_NEW\_HALF} = \frac{700mill}{22km} * \left(\frac{22km}{17km}\right)^{0,08} * 17km = 552mill$$

$$Cost_{\_NEW\_HALF\_TOTAL} = 2 * Cost_{\_NEW\_HALF} = 1104mill$$

In this case the budget correction factor would be an estimated **1.02**, corresponding to 1,104/1,082. As seen, the learning curve theory can adjust budgets in each direction, as it uses data *relative* to the new values.

It is therefore highly important to keep in mind that the different formulas for the effect of repetition/learning all need the proportion or scale between the historical base projects and the new one. This should be taken into consideration when assessing the possible size of the effect of repetition for various building and construction works.

A performance datum that gives e.g. time consumption per unit can be strongly influenced by the specific quantity that the measurement is based on. Due to the possible effect of repetition any description of works is not complete unless a) quantities before measurement, b) quantities measured; and c) quantities left are given. Thus:

$$800 + \underline{500} + 2000 = 3300$$

means that the measuring concerns 500 units after completion of 800 units, and that 2,000 units remain to be produced.

Especially this latter condition is important as effects of repetition and learning, using the learning curve theory, only can be established if the exact starting point is given.

Further work

In the light of the difficulties of finding relevant and suitable studies – even on an international scale – we recommend that resources are set aside to facilitate an empirical study of the København-Ringsted project. The purpose of the project would be to establish the size of the possible effect of repetition in large infrastructure projects to provide a suitable benchmark for future investments. Further, the purpose of the project would be to establish which calculation factors are the most appropriate to address and how to apply them systematically in the new budgeting model of the Public Transport Authority.

7. Addendum

The present chapter constitutes an addendum to the main report and is written four month after the main report was handed over to the Public Transport Authority.

The chapter contains a series of processed comments given by a panel of international experts, who have taken the report under critical review for validation and quality assurance purposes.

The Danish Building Research Institute, Aalborg University would like to thank:

- Professor Christian Brockmann, University of Applied Sciences Bremen, Germany.
- Head of Department Per Olav Laukli, Multiconsult, Norway.
- Dr.Scient Steen Lichtenberg, Lichtenberg & Partners Management consultants, Denmark.
- Partner and Head of Research Simon Rawlinson, Davis Langdon LLP, Construction Cost and Project Managers, United Kingdom.
- Senior Lecturer Gerard De Valence, School of the Built Environment, University of Technology Sydney, Australia.

Comments on the quantification of the effect of repetition

Throughout the main report, we have worked with an estimated effect of repetition in building and construction works in the range of 6 % to 12 %

In general reviewers comment that an estimate of a repetition effect of 6-12 % per doubling echo their experiences; however similar to the conclusions we have drawn in the main report, these benefits depend on a variety of other factors like the structural complexity, continuity, duration and size/quantities.

As a general observation, several reviewers argue (in-line with the provisos taken in the main report) that within this field of research, not very many results are published, which make estimates difficult.

On the limits of effects of repetition, it is noted by one reviewer that ample national data on very specific construction works or activities (e.g. formwork), shows that improvements often stop after a limited number of repetitions (typically ca. 10 repetitions) and that this has to be taken into consideration.

Comments on methods applied and sources used

A specific observation from the review is that the mathematical formulas and the curve shapes presented in the main report are too detailed, as empirical data will always be somewhat "muddy" and this calls for simple approximate formulas. As it is stated:

> *"The discussion on the formulas is to me academic because it assumes precise data. While the discussion is still helpful, the conclusion should be as above."*

Further, it was noted that, on the face of it, some of the empirical evidence for the experience curve is not convincing. In particular the rate of cost decay related to size for the road project described by Estache and Limi (2008) is argued to be less credible today in a European construction industry, where even a 10 km stretch of road would represent a major, multi-million Euro opportunity.

Similarly, it is argued that the results for housing described in the 1965 Economic Commission paper may have resulted from the comparison of different construction techniques, where large scale system building that was common in Europe in the 1960s and 70s resulted in conditions, where a diseconomy of ‘small scale’ may have been quite pronounced. The step change in this analysis may be as a result of alternative factors of production – particularly capital – rather than an experience curve. Nevertheless, it is stated that the work despite these flaws constitutes an excellent report in what is argued to be "*clearly an under-investigated area.*"

Factors influencing effects of repetition

In the main report, we have listed a number of factors that we argue should be taken into consideration when estimating the potential of achieving benefits from effects of repetition.

Here reviewers argue that "technology," "skills" and "organisation" should be included in the list. As it is said:

> *"You should include technology, complexity somehow picks the concept up, but it is not clear enough […] When employing new technologies, there is a quantum leap in learning, followed by a steep learning curve."*

Furthermore, on the topic of skills, the following argument is put forward that:

> *"The higher the skill and the more routine the work, the less is learning."*

On the topic of organisation, the argument rests on the empirical observation by one of the reviewers that projects where all activities are conducted under one single command perform better than projects consisting of several independent units.

On the factor "mechanisation" it is argued that it has only a slowing influence if taken as a constant in the formulas. A reviewer argued that if one allows for learning in mechanisation (i.e. improvements of equipment), cost reduction will be accelerated.

We concur with these statements; however we maintain that in *early budgeting situations*, such as the one that we are facing in the Copenhagen-Ringsted case, which is the centre of attention in the present paper, it can be highly or indeed impossible to assess these exact factors *ex ante*.

In a subsequent work planning and monitoring situation, where on-site construction works and activities are conducted, collection and assessment of data according to these factors would however be highly recommendable.

Comments of concepts of learning, experience and scale

Throughout the main report, we have used the term "learning effects/curves" etc. as a collective name for the variety of different efforts resulting in effects of repetition. Reviewers however suggest that it might be relevant to differentiate more rigorous between:

- Learning.
- Experience.
- Structure.

Thus, there are structural influences and learning influences. As stated by a reviewer:

> *"Lower cost for bigger projects is not necessarily tied to learning. The bigger the project, the smaller the influence of fixed cost on unit cost, this is the structural influence."*

Even though, we have used the concept of structural influence at the end of the main report, reviewers lacked a clear definition hereof, which is seen above.

Furthermore, it is suggested that there should be distinguished between learning and experience curves. Drawing such a distinction would posit "*everything in the technical/management improvement categories*" as experience effects, whereas learning effects would contain procssesual and operational improvements.

Comments on the report in general

Apart form the above points of criticism; all reviewers agree that the report is very solid and valuable. Selected comments on the report in general are given below:

- You have produced an excellent report in what is clearly an under investigated area - many congratulations on your work.
- I trust that you will not object to our citing your excellent work in our own report.
- It was interesting for us to get the opportunity to be involved in your study.
- Having the opportunity to review your report has actually been very useful for me […] Your work has brought to my attention empirical research that will help us develop our response to the client's requirement. Hence this review has been mutually very beneficial.
- I think you have written an important and interesting paper. I learned a lot of new ideas: Congratulations!

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Appendix A

Empirical examples on the size of the learning/repetition effect in building and construction works.

Highway costs

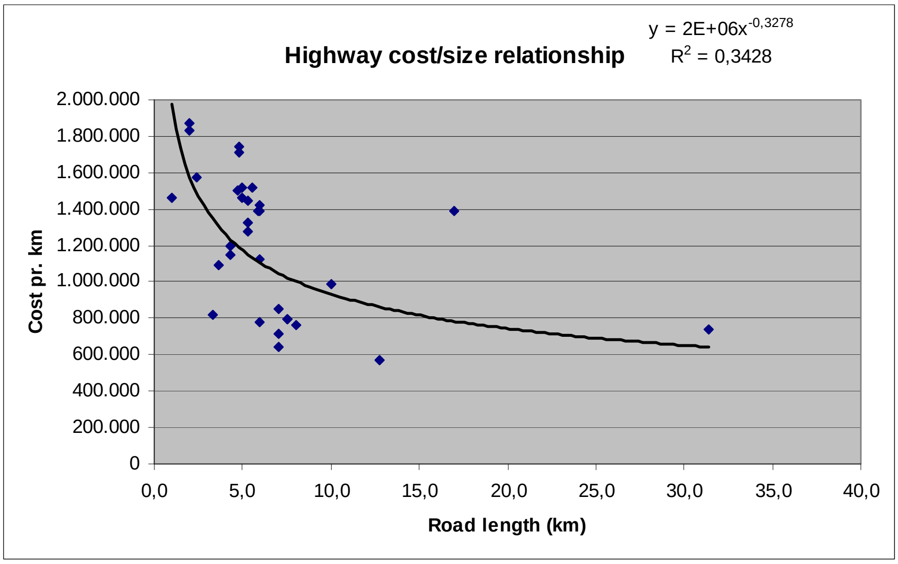

Figure A-1. Cost/size relationships in construction of new 2L highways in Poland (based on data from the World Bank, 2002).

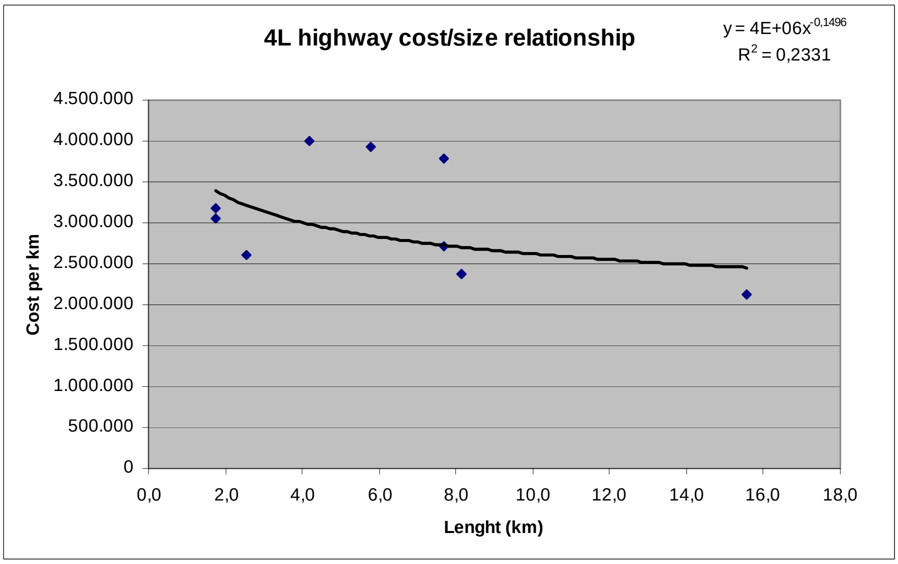

Figure A-2. Cost/size relationships in construction of new 4L highways in Poland (based on data from the World Bank, 2002).

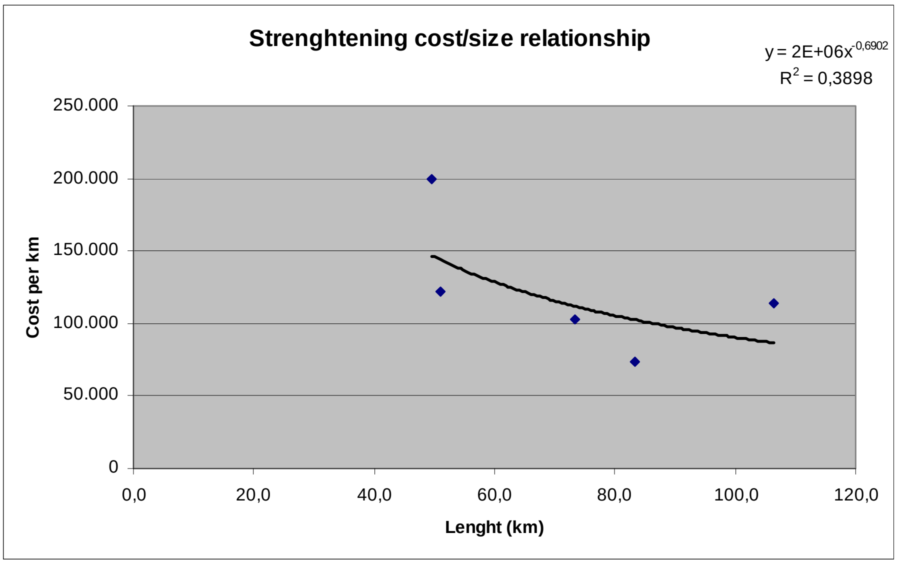

Figure A-3. Cost/size relationships in strengthening roads in Bangladesh (based on data from the World Bank, 2002).

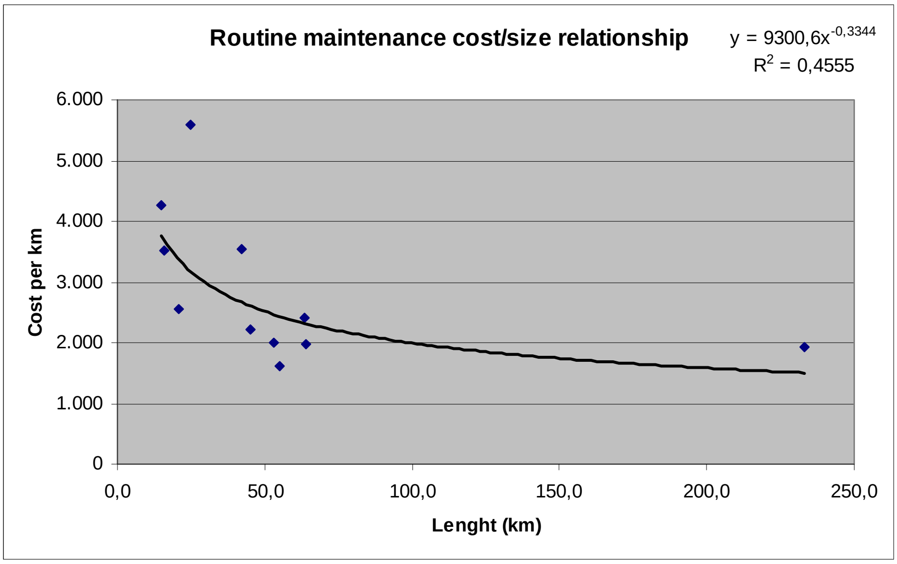

Figure A-4. Cost/size relationships in routine maintenance of 2L highways in Uganda (based on data from the World Bank, 2002).

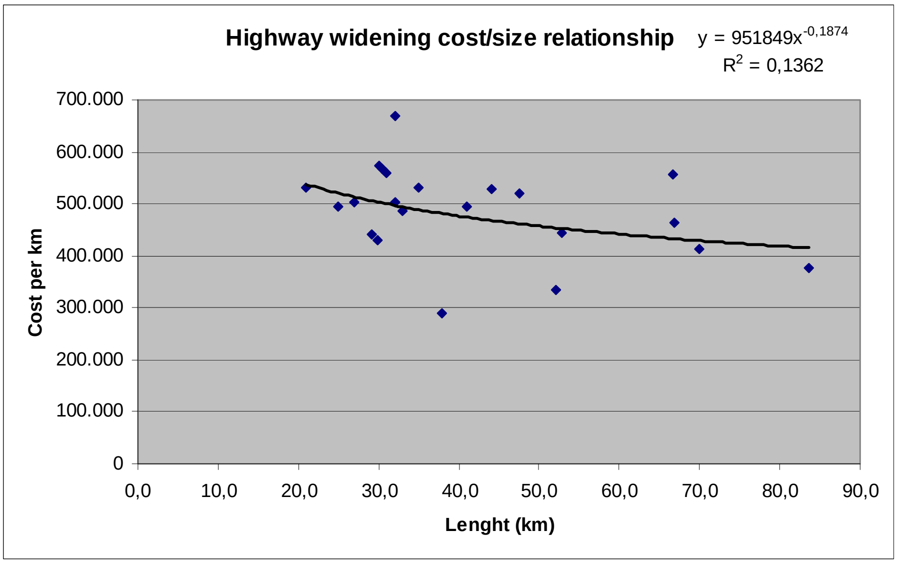

Figure A-5. Cost/size relationships in highway widening projects in Thailand (based on data from the World Bank, 2002).

Railway costs

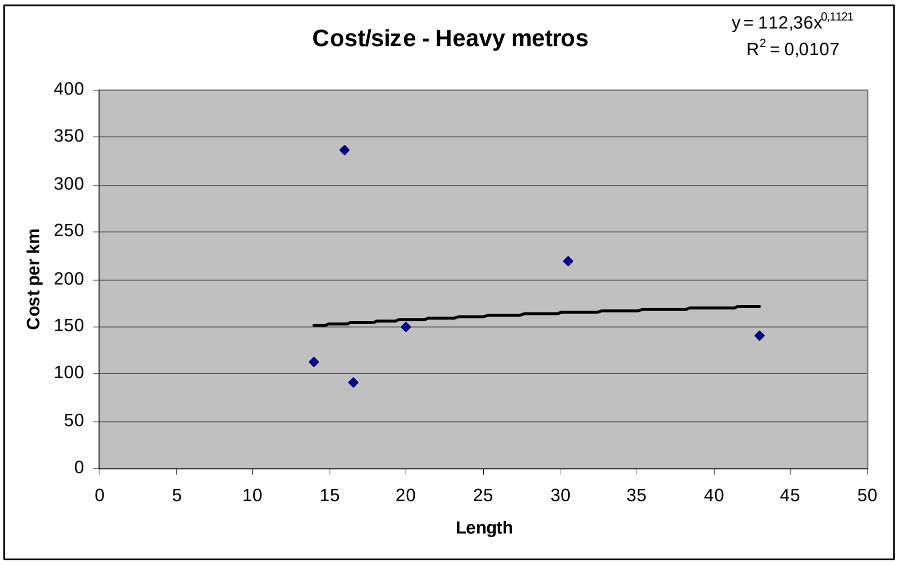

Figure A-6. Cost/size relationships for heavy tunnelled metros (based on data from Railway Technical Web Pages).

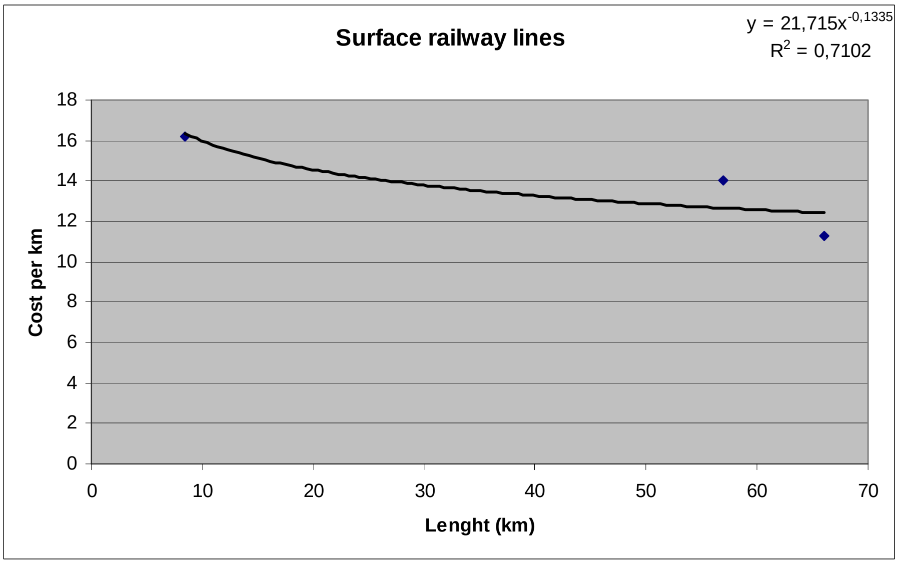

Figure A-7. Cost/size relationships for surface railway lines (based on data from Railway Technical Web Pages).

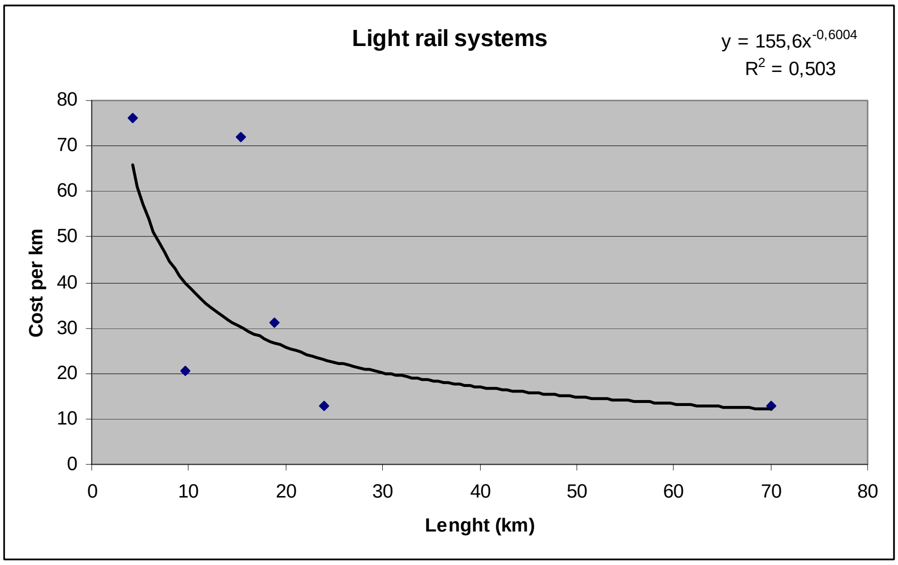

Figure A-8. Cost/size relationships for light rail systems (based on data from Railway Technical Web Pages).

Social housing costs

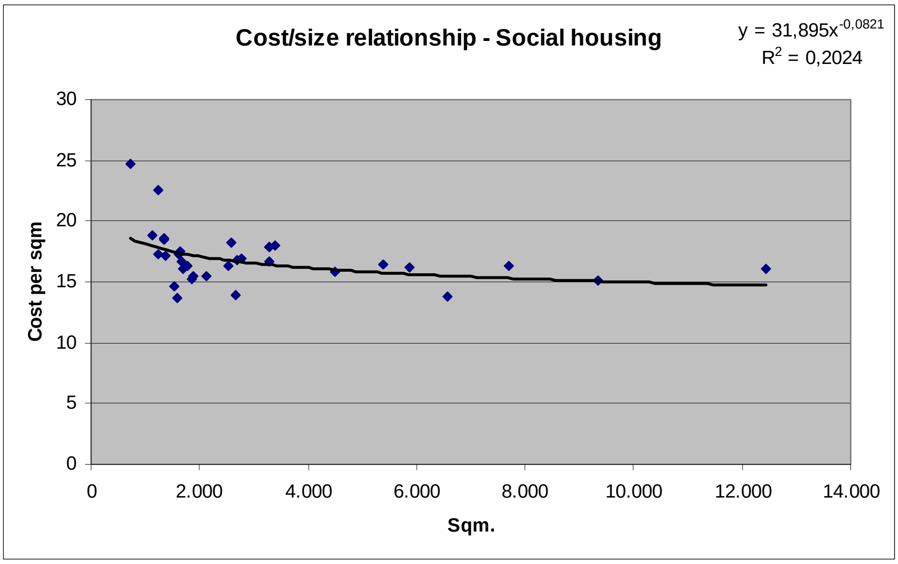

Figure A-9. Cost/size relationship for social housing in Copenhagen (based on data from the Ministry of the Interior and Social Affairs. Calculations are conducted by the authors).