WORK EFFICIENCY EVALUATION MODEL

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Abstract

As for a backhoe, generally, the work efficiency is utilized as one of terms to calculate the work capacity. As the case stands, evaluation metrics such as performance of work tasks, operational skill levels and energy-saving effects are usually and frequently represented by qualitatively volumetric indices of capacity. This paper proposes the work efficiency evaluation model that quantitatively visualizes work efficiency in terms of work control factor, work time factor and workability factor, and serves users with commentary information. Here, physical factors such as work and power are introduced to calculate the workability factor. The commentary information consists of management information, operator bearing, complementary explanation, and early warning, which are accompanied with work commands. It is anticipated that the work efficiency evaluation model could perform rationally purposive evaluation, instructions and education as for performances of work tasks, operational skill levels and energy-saving effects.

KEYWORDS: work control factor, work time factor, workability factor, commentary information.

PURPOSE

As the case standards, evaluation metrics such as performance of work tasks, operational skill levels and energy-saving effects are usually and frequently represented by qualitatively volumetric indices of capacity. This paper proposes the work efficiency evaluation model for a backhoe, which are operated through a work line of digging, loading, hauling and dumping. Generally, work efficiency is utilized as one of terms to calculate work capacity of construction machinery. The work efficiency evaluation model aims to visualize work efficiency quantitatively in terms of work control factor, work time factor and workability factor, and serves users with commentary information. Here, physical factors such as work and power are introduced to represent the workability factor. The commentary information consists of management information, operator bearing, complementary explanation, and early warning, which are accompanied with commands regarding job units. First, this paper delineates a factor breakdown structure of the work efficiency. Secondly are reported lessons learned from the case studies on pitch time and backhoe stick movement. Thirdly, this paper gives arguments about a description of operator bearing and the complementary information. Finally, this paper presents remarks and further works.

FACTOR BREAKDOWN STRUCTURE OF WORK EFFICIENCY

As well known, production formula regarding a backhoe is represented by the following equation:

$$Q = \frac{3{,}600 \times q \times k \times f \times E}{Cm}, \quad (1)$$

where "Q" is production per hour (in m3/hr), "q" is payload (heaped capacity in m3/trip), "k" is bucket fill factor, "f" is earth volume conversion factor, "E" is work efficiency factor, and "C_m" is cycle time (in second).

If numeric value of actual performance of "Q" and "C_m" should be gained someway, then the actual value of the work efficiency "E" could be derived from the following equation:

$$E = \frac{Q \times C_m}{3{,}600 \times q \times k \times f}. \quad (2)$$

Suppose here that "q", "k", and "f" are given by some relevant references, respectively. Generally, numeric values of these are published in the many references concerned.

Now, we delve a little deeper into how the work efficiency factor breaks down into concrete terms. Here, supposed that the work efficiency factor consists of work control factor, working time factor, and workability factor as shown in the following equation:

$$E = E_1 \times E_2 \times E_3, \quad (3)$$

where "E" is work efficiency, "E_1" is work control factor, "E_2" is working time factor, and "E_3" is the workability factor.

The work control factor is defined as

$$E_1 = 1 - R, \quad (4)$$

where "R" shows a degree of negative impact influence against work control, which depends on the following matters:

- Labour force such as worker skill and motivation,

- Resource allocation and maintenance, for example, selection, operation, and maintenance of equipment, and

- Construction plan and management such as planning, job layout, supervision and coordination.

The work time factor is defined as:

$$E_2 = \frac{T_r}{T_o}, \quad (5)$$

where "T_r" is real working time, and "T_o" is operating time that equals to the sum of real working time, travelling time, idling time, waiting time in working, and others. Said another way, this means an operating ratio (Nishigaki, et al., 2010).

Basically, we contemplate here physical factors such as work and power to encompass the working ability factor. As well known, energy is represented by

$$Energy = \frac{1}{2} mv^2, \quad (6)$$

where "m" is mass of object and "v" is velocity, and then power is given by:

$$PWR = \frac{Energy}{t}, \quad (7)$$

where "PWR" is power, and "t" is time. In addition, work of mobile entity is represented by:

$$Wrk = m \times \alpha \times d \quad (8)$$

where "Wrk" is work, "α" is acceleration, and "d" is distance moved of mobile entity.

The workability factor is defined as:

$$E_3 = 1 - p \quad (9)$$

where "E_3" is workability factor; and "p" is pitch time.

Here, the pitch time is represented by the following equation:

$$p = \frac{T_r}{Wrk} \quad (10)$$

Since the pitch time could be a real working time per throughput, it means a degree of difficulty to work a job unit out. By the way, the reciprocal of the pitch time should likely show the power gained by

$$PWR = \frac{Wrk}{T_r}. \quad (11)$$

LESSONS LEARNED

Degree of Difficulty to Work Out

Figure 1 shows an example of a time series graph of both operating ratio and pitch time as to one of backhoes being operated in a haul work for removal of rocks such as gravel, pebble, and boulder being deposited behind a check dam. In this operation, approximately 22,000 tones of rocks should be hauled to the destination, which is approximately 9 km away (Nishigaki, et al., 2010).

It can be seen from Figure 1 that changes in the operating ratio might be inversely proportional to those in the pitch time. Generally, as a pitch time of an operation might become larger, this operation might get less and less efficient. The work cell with the large pitch time could be a bottleneck of the work line.

Having said that, pitch time shows a degree of difficulty to work a job unit out, and its reciprocal likely shows power, that is, a degree of easiness to work a job unit out. Thus, we could grasp a degree of difficulty to work a job unit out by observing transition of a pitch time, and conversely get hold of a degree of easiness to work a job unit out by tracking the power.

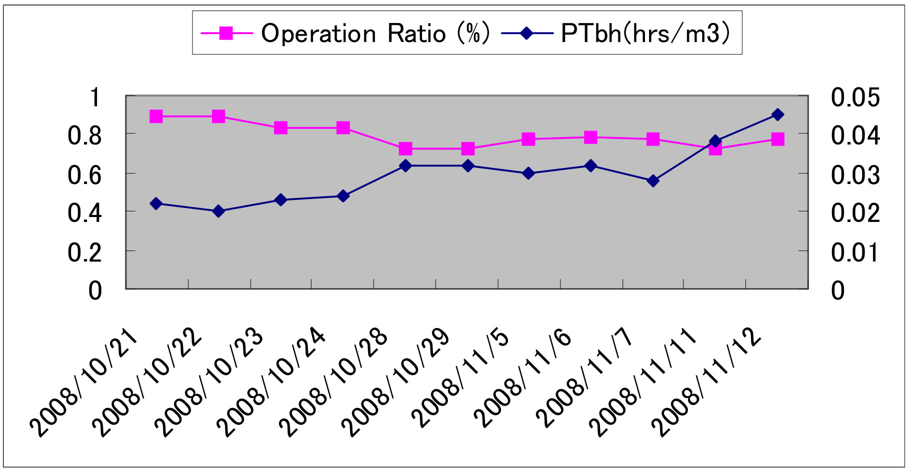

Figure 1: Time Series Graph of both Operating Ratio and Pitch Time as to one of Backhoes

Analysis of Backhoe Stick Movement

Backhoe operations consist of stopping/stalling, positioning, adjusting posture, extending, retracting, raising, lowering, curling, scooping, crowding, and swinging, and so on. Appearance and motion being required in backhoe operation could be characterized by the keywords of “ease”, “smooth”, “continuous”, “consistent”, and the like.

In order to gain a priori knowledge about the appearance and motion, we would review backhoe stick movement of cutting and dumping operations with an emphasis on accelerations, which is one of terms of the work. For simplicity, it is supposed here that the mass and moving distance of the mobile entity, that is to say, the stick, equal to the numeric value “1”, respectively. Actually, the mass may depend on both the heaped capacity of bucket size being utilized and type of material being handled. Moreover, the distance moved of mobile entity may be different by a degree of operating skill. Put it in another way, the supposition here means no-consideration about any difference among types of materials and between skilled and unskilled operations.

The appearance and motion with the above keywords might be represented by numeric values derived from variation of acceleration, which is yielded by a backhoe stick movement and is measured in this analysis. For simplicity, are focused on cutting soil with a bucket and dumping it on to a pile, which are the fundamental operations of a backhoe. Moreover, from a viewpoint of cost performance, are utilized a radio control toy model of a backhoe, an acceleration sensor and a data logger as shown in Figure 2.

Here, the sequence of cutting and dumping operations is composed of raising boom as extracting stick (motion 1), curing bucket out as extending stick while lowering boom a bit (motion 2), curling bucket in as extracting stick while lowering boom a bit, and subsequently raising boom a bit (motion 3), swinging boom horizontally toward the left site and stalled at an angle of about 45 degrees (motion 4) , and curing bucket out as extending stick while fixing boom for dumping (motion 5). The sequence of these is simulated by the radio control toy model. And then, the accelerations, which are yielded by the movement of the stick in the sequence, are measured by the acceleration sensor and stored in the data logger.

Motion1: Raise boom as extracting stick

Motion 2: Curl bucket out as extending stick while lowering boom a bit

Motion 3: Curl bucket in as extracting stick while lowering boom a bit, and subsequently raising boom a bit

Stick extracted before swing boom

Position for dumping after swing boom

Motion 4: Swing boom horizontally toward the left side and stalled at an angle of about 45 degrees

Motion 5: Curl bucket out as extending stick while fixing boom for dumping

Figure 2: Sequence of Cutting and Dumping Operation

Figure 3 shows acceleration-time graph as for the cutting and dumping operations as mentioned above. In the reference system, the X axis “red line” designates the horizontal direction from side to side, the Y axis “blue line” the vertical direction, and the Z axis “green line” the back and forth direction from a viewpoint of a operator.

It can be seen from Figure 3 that the variations of the accelerations are characterized into:

- Along the vertical direction, it is likely to change upward with fluctuations in close succession in the motion 1 and with the large jerks in the motion 2, and conversely, downward as impelling in the motion 3,

- Along the back and forth direction, it is likely to descend with large fluctuations in a moment, probably effects by reaction or inertial forces, in the motion 1, and subsequently, change downward in the motion 2, and conversely, upward as impelling in the motion 3,

- Along both the vertical direction, it is likely to fluctuate with comparatively large amplitude in the motion 4,

- On the contrary, it is likely to oscillate short in the motion 4 along the back and forth direction,

- Along the horizontal direction from side to side, it is likely to oscillate in close succession through the sequence.

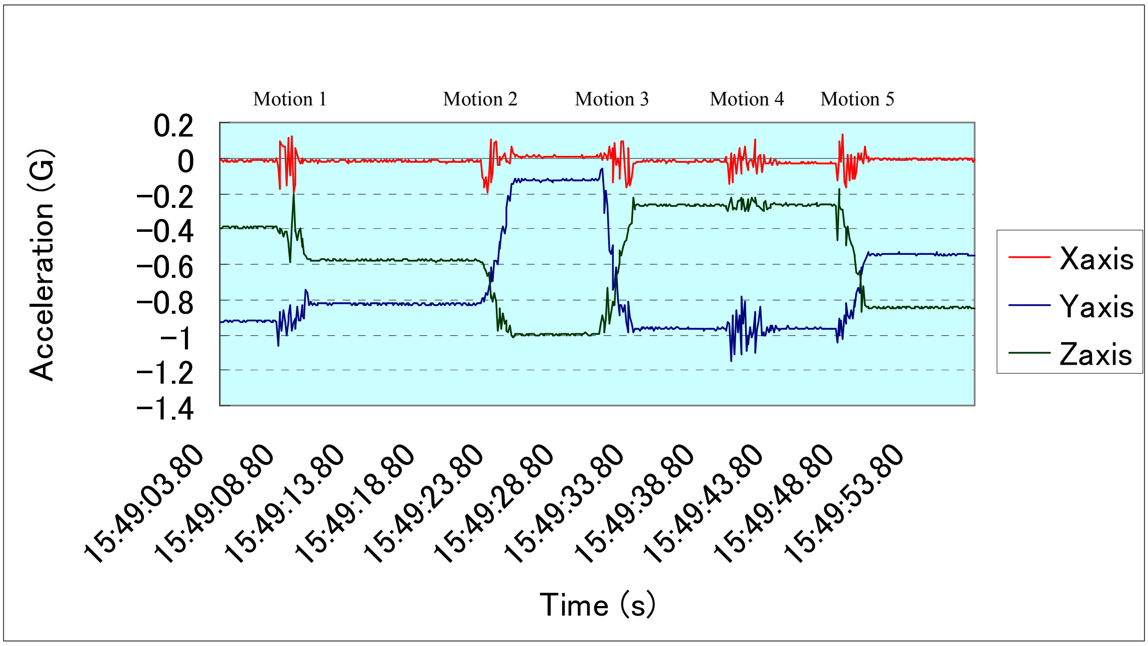

Figure 3: Time Series Graphs of Transition of Acceleration

The histograms of both the accelerations measured and the jerks calculated are made as for the each axis as shown in Figure 4. Looking at them, here are reported the distribution shapes with distinct characteristics below.

As for the distribution shapes of the accelerations along the horizontal direction from side to site, all the mean values are almost closed to the zero. In the each motion, is found a distribution shape skewed to the right.

As for the distribution shapes of the jerks along the horizontal direction from side to site, all the mean values of the jerks as for all the motions are almost closed to zero. Looking in the skewness, in the motion 1 and the motion 3, are seen distribution shapes skewed to the left, respectively. Conversely, in the other motions, are found distribution shapes skewed to the right, respectively.

As for the distribution shapes of the accelerations along the vertical direction, in the motion 1 and the motion 4, are found bell shaped distributions with more or less the same sized tails on each side, respectively. On the other hand, in the motion 2 and the motion 3, there are distribution shapes with two polarized heaps, respectively. In the motion 3, is looked a ski-jump shaped distribution that is skewed to the left with something like the floor effect. On the contrary, in the motion 5, is shown a J shaped distribution that is skewed to the right with something like the ceiling effect.

All the distribution shapes of the jerk along the vertical direction have a high heap. Moreover, all the mean values of the jerks as for all the motions are almost closed to the zero. In the motions except the motion 3, have a distribution shape skewed to the left, respectively. On the contrary, in the motion 3, is looked like a distribution shape skewed to the right.

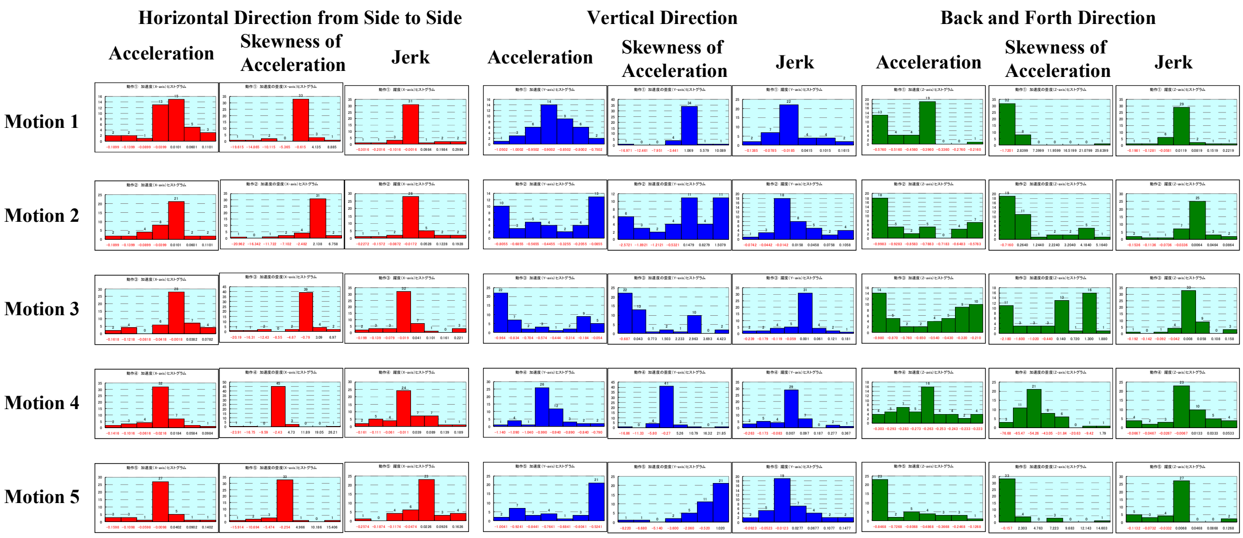

Figure 4: Histograms of the Acceleration and the Jerk

As for the distribution shapes of the accelerations along the back and forth direction, all the mean values of the jerks are almost closed to the zero. In the motions except the motion 3, are seen distribution shapes that are skewed to the left. Looking in the skewness, ski-jump shaped distributions with something like the floor effects are found in the motion 2 and the motion 5. On the contrary, in the motion 2 and the motion 3, are found distribution shapes with two polarized heaps, respectively.

As for the distribution shapes of the jerks along the back and forth direction, all the mean values of the jerks as for all the motions are almost closed to the zero. In the motion 1 and the motion 5, are seen distribution shapes skewed to the left, and conversely in the other motions, are found distribution shapes skewed to the right, respectively.

Thus, the workability factor, focusing on the acceleration and the jerk, could depict the appearances and motions of cutting and dumping operations. Put it another way, it is conjectured that backhoe operations could be classified by variations of accelerations as for the each axis. Likewise, it might be possible to characterize operator's skill levels by variations of jerks as for the each axis.

DESCRIPTION OF OPERAOR BEARING

As argued earlier, workability factor based on pitch time and acceleration could be capable of depicting an operator bearing. Examples of information on the work efficiency include a degree of work difficulty, and an operator bearing.

Degree of Work Difficulty

As described earlier, the pitch time means hours worked per throughput in the each work cell. The pitch time could show degree of difficulty to work a job unit out. On the contrary, the reciprocal of the pitch time, that is, the power, means degree of work easiness.

Operator Bearing

Operator bearing means peculiarities of appearance and motion in operating a backhoe. The good performance should be shown by a movement with ease and/or a smoothness of movement, which could have the following characteristics:

- Standard deviation of velocity might be small,
- Maximal numeric value of acceleration might be small,
- Absolute value of minimal deceleration might be small,
- Standard deviation of acceleration and deceleration might be small,
- Skewness (direction of asymmetry) of distribution shape of acceleration might be nearly zero, and
- Average of the squared jerk along the trajectory from one point to another might be small.

These characteristics above could be represented by the workability factor as shown by the equations from (6) to (11). Especially, it is worthy to focus on work. The work depends on mass, acceleration and distance moved as shown in the equation (8). In the case study as reported in the previous section, we focused on only the acceleration. From now on, it needs to consider the mass and the distance moved of mobile entity.

COMMENTARY INFORMATION

The commentary information consists of management information, operator bearing, complementary explanation, and early warning. It is indirectly related to job unit and event, and is coupled to commands for operations as shown in Figure 5.

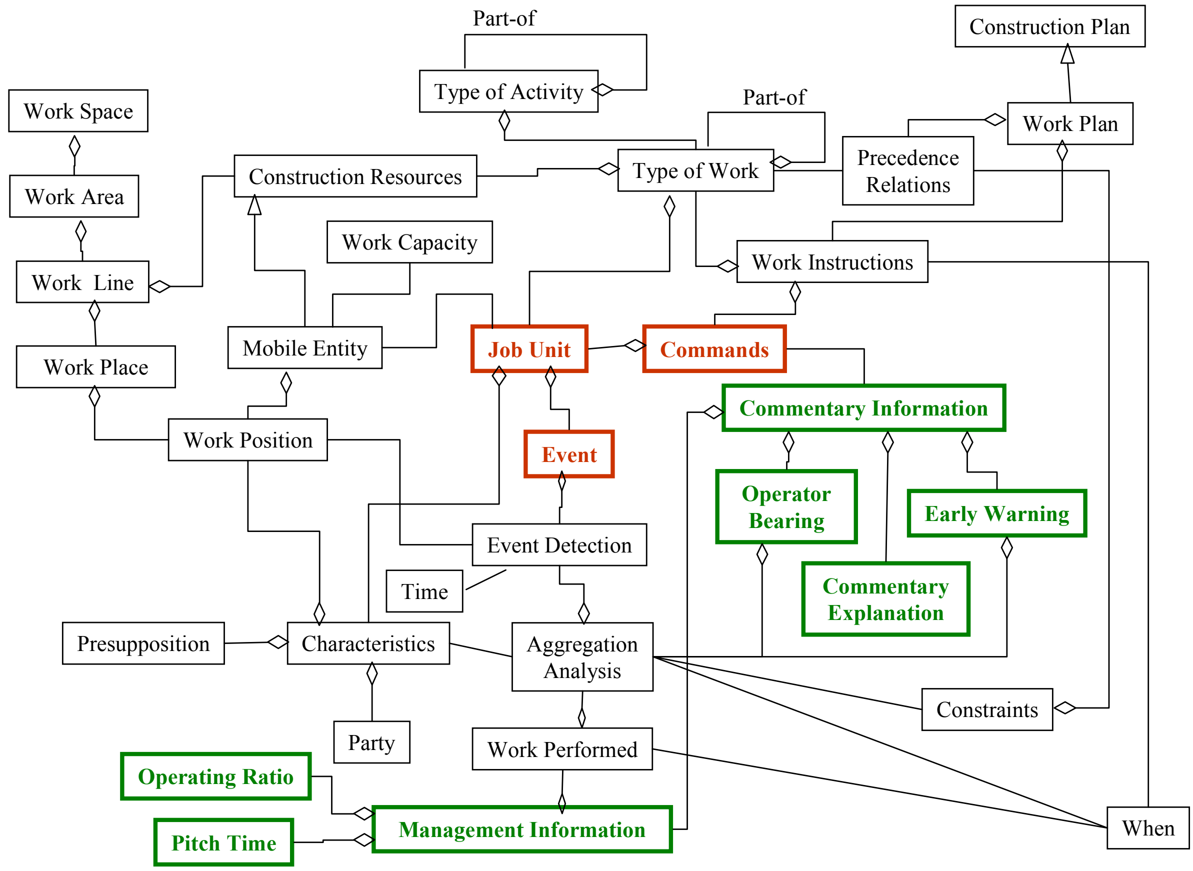

Figure 5: Position of Complementary Information in Data Model

The commentary information consists of representations or interpretations as to the matters as follows:

- Management information such as pitch time, operating ratio,

- Operator bearing such as statistical values of accelerations and jerks,

- Early warnings against impending risks such as alarm by collision detection, and incident command to take shelter, and

- Commentary explanation such as safety instructions and practice guides.

Basically, the commentary information would be coupled to the work commands concerned, and shown operators while working, and could make it easier for them to understand the work environment, to access the work situation and the current operation, and to make decisions and affect their control with the objectives of increasing construction efficiency and energy-saving.

SUMMARY AND FURTHER WORKS

As described in this paper, the work efficiency evaluation model is composed of the work control factor, the work time factor, and the workability factor. In addition, this paper presents the workability factor that is represented in terms of pitch time, power, and work. The pitch time shows a degree of work difficulty, and conversely, its reciprocal value could likely mean the easiness of work. In addition, as a priori study, is analyzed a backhoe stick movement in the cutting and dumping operation. In consequence, it could be said that the workability factor would represent the operator bearing.

Put it together, the work efficiency evaluation model would give a detailed visibility into appearance and motion in backhoe operations. Moreover, it is expected that information on work efficiency could yield the following effectiveness:

- It enable us to grasp current state and construction efficiency of mechanized construction in progress and to make decision on timely basis; and

- It is capable of performing rationally purposive evaluation, instructions and education for construction practices as to performances of work tasks, operational skill levels and energy-saving effects.

From now on, in order to encompass the work efficiency evaluation model, we would like to conduct field experiments of backhoe operations such as slope shaping, trenching and loading. In this field experiments, both mass of material being handled and distance moved of mobile entity will be also considered. Given the accumulated experience of these field experiments, we will plan to develop a guide and instruction system, which is capable of providing resident engineers, site manager, and operators with information on line of balance, operator bearing, and commentary information based on the actual data.

REFERENCES

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