CONTENTS

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PARALLEL KINEMATICS MACHINE TOOLS: HISTORY, PRESENT, FUTURE

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Abstract: Recently parallel kinematics machine tools attracted the attention due to their theoretically high motion dynamics potential, accuracy and stiffness due to their closed loop structure and no error accumulation characteristics. This paper gives a survey of the development of the parallel kinematics machine tools, their performances and their practical application compared with serial machine tools.

Key words: parallel kinematics machine tools, performances, application

1. Introduction

Parallel kinematics manipulators have attracted the attention in research institutions and industry due to their high theoretical dynamics potential, structural rigidity and high accuracy due to the closed kinematic loops and no error accumulating characteristics.

Parallel manipulator also could be named as hexapod, a Stewart platform, Gough platform, Stewart-Gough platform, a parallel kinematic machine (PKM) or a parallel robot.

The first prototypes of parallel kinematics machine (PKM) tools were introduced to the public in 1994 by Ingersoll and Ginddings & Lewis (Fig.1 and Fig. 2).

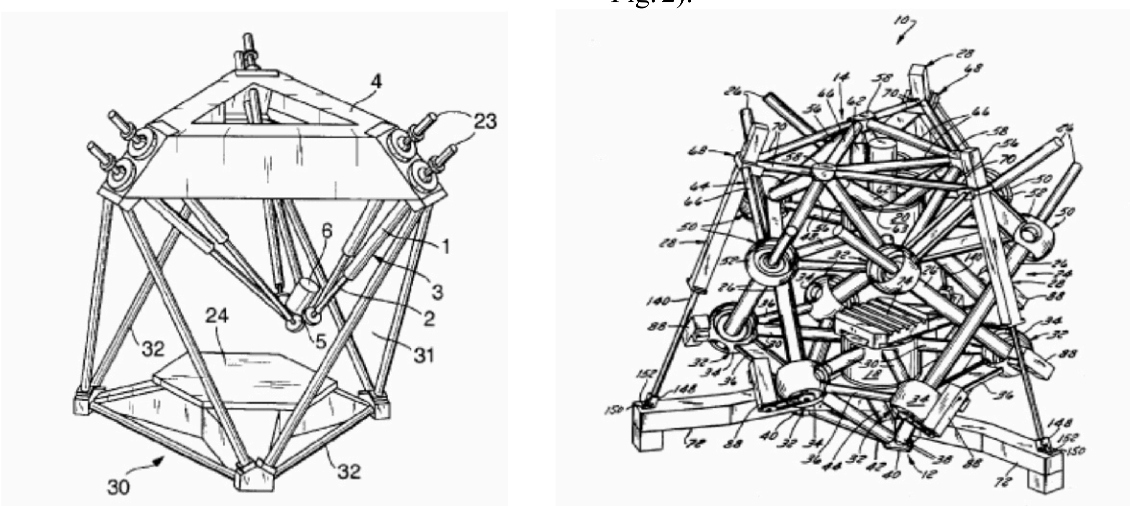
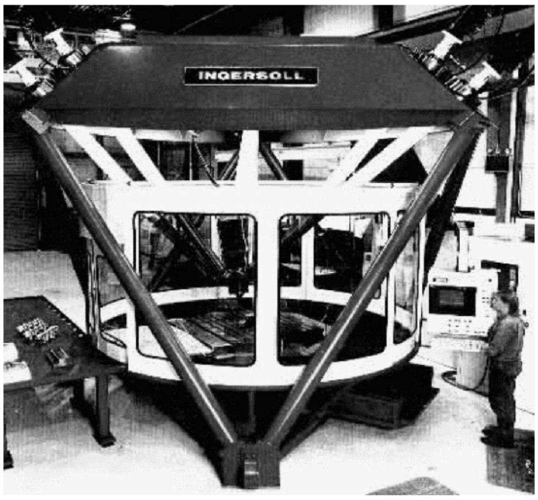


Fig. 1 Schemes of parallel kinematics machine tools a) Ingersoll's "Octahedral Hexapod" b) Giddings & Lewis' "Variax" [54]



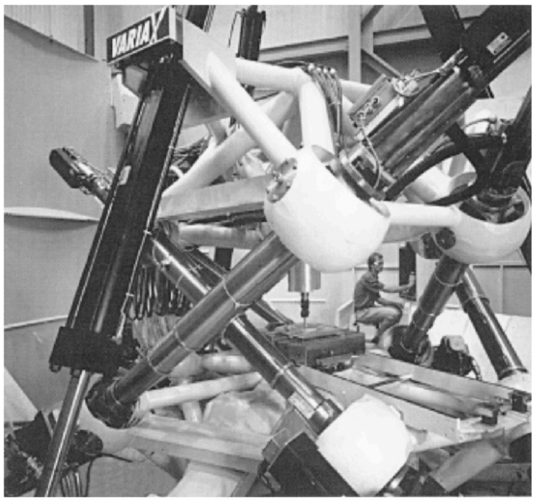


Fig. 2 Photos of parallel kinematics machine tools a) Ingersoll's "Octahedral Hexapod b) Giddings & Lewis' "Variax" [54]

During the last decade, according [27] more than 100 different parallel mechanical architectures have been built, mostly as prototypes or academic studies.

Although more than 10 years passed since the first commercial parallel kinematics machine tools were introduced, they are not widely accepted in the industry.

There are two reasons for that.

First, from the beginning of their appearance it became obvious that implementation of their theoretical capabilities in practice introduces many new problems.

The second reason are the psychological arguments like:

- lack of trust in the new, strange looking technology,

- reluctance to be first to try out the new technology,

-lack of accepted standards for assessing the users value of the parallel kinematics machine tools [38].

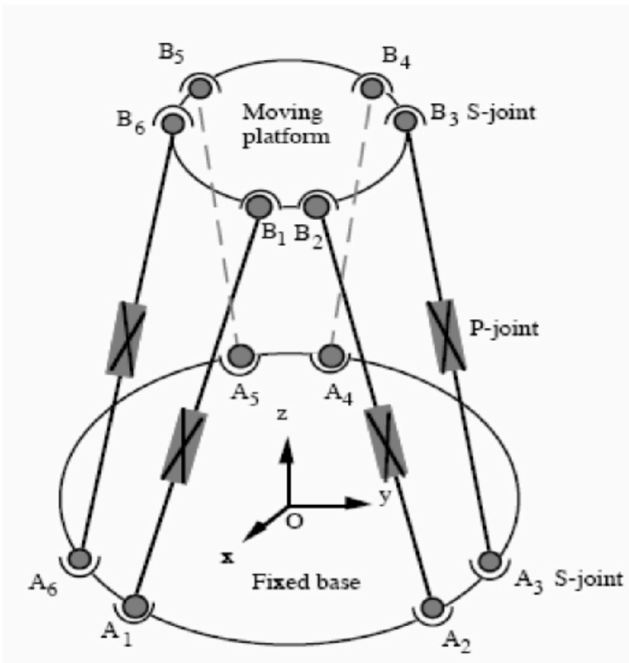
Additionally, there are highly antagonistic opinions about parallel kinematics machine tools technology. The concept is claimed to be inferior to serial machines and practically not useful [42] or called the innovation focus on the METAV fair 2000 in Düsseldorf, Germany [23].

The aim of this paper is to give a survey of the development of parallel kinematics machine tools and their characteristics compared with serial machine tool.

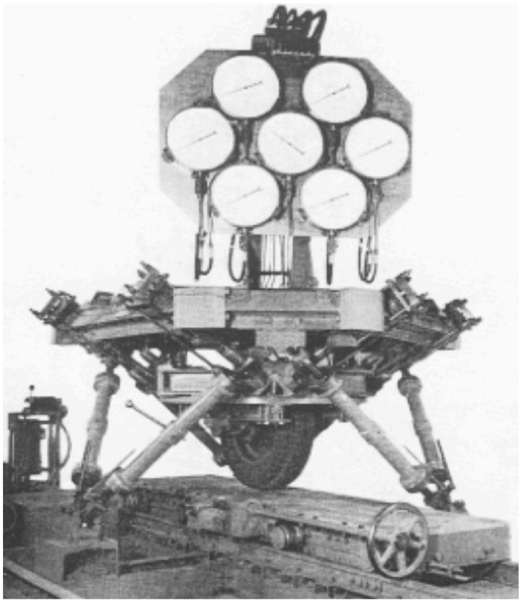
2. Historyical development

Historically, parallel mechanisms (closed - chain structures) have attracted the interest mostly of mathematicians as they offer interesting problems. Some theoretical problems linked to this type of mechanisms were mentioned as early as 1645 by Christopher Wren, then in 1813 by Cauchy and in 1867 by Lebesgue. One of the main theoretical problems in this field was singularity analysis. But clearly at this time the technology was not able to deal with any practical applications of this type of mechanism.

In the 50's and 60's of the last century "hexapod" type parallel mechanisms (Fig.3 a), were used in motion simulators: tire test machine [10] (Fig.3 b) and flight-simulator [41].



a)



b)

Fig. 3 a)"Hexapod" type parallel mechanism
b) Gough's tire tester

Even in the 60's of the last century the application of such structures as machine tools has been discussed, but rejected due to the lacking of control technology [46].

In the 1980's parallel kinematics structures attracted the interest of robotic community.

The most successful parallel kinematic robot structures are the Delta robot (Fig. 4), designed in 1980's by Prof. Reymond Clavel (professor at EPFL École Polytechnique Fédérale de Lausanne) and Tricept robot (Fig.5) designed and built by Karl-Erik Neumann in 1987.

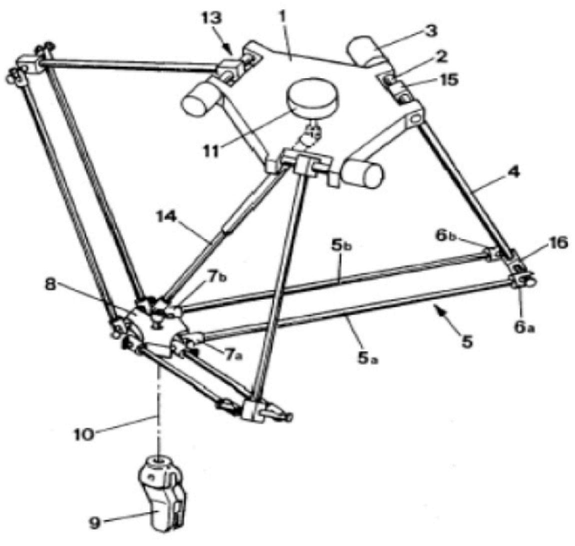


Fig. 4. Schema of the Delta robot
(from US patent No. 4,976,582) [49]

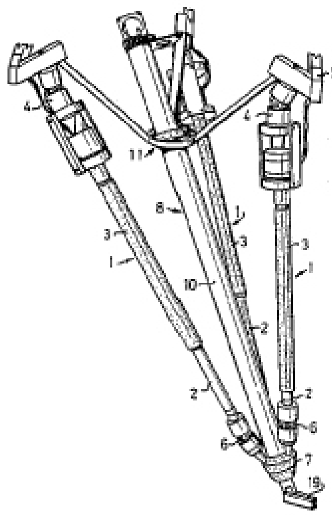


Fig.5 3-DOF Parallel kinematic robot Tricept
(US Patent No.: US 4,732,525) [49]

Both structures have had a commercial success and now can be found in different industrial applications [3, 29,30].

In 1994 the first prototypes of parallel kinematics machine tools were presented by Ingersoll and Ginddings & Lewis at the International Manufacturing Technology Show in Chicago (Fig.1 and Fig 2.). These machines were realised as Gough platform and their purpose was 5-axis milling.

In industry, product originality counts much less than product performance. Thus, building a successful product requires team work - a partnership between potential customers, industry and academia. Unfortunately, this fact was ignored by industry. Companies, such as Giddings & Lewis and Ingersoll, with long-standing expertise in machining, decided to go alone. But they have failed with their parallel kinematics machine tools, even they were the first to deliver them to the market. They simply failed to deliver the promises of superior accuracy. Overlooked problems such as thermal expansion, vibrations, and system complexity are some of the reasons.

The origins of this failure are at the companies' approach which was not application - but product -driven. Here is this futuristic six-legged structure used in simulators, let us turn it into a machine tool [4].

In the following years, many new prototypes of machine tools for milling and other processes have been developed in the research institutes and industry, but mainly intended do study the fundamentals of this new technology, instead of market products. In addition, a large number of patents related to parallel kinematic machines have been applied.

Today, parallel kinematics machine tools, slowly but surely, entering the commercial market and are already established in niche applications [14,13, 20].

3. Classification of parallel kinematics machines

A parallel manipulator is a closed-loop mechanism in which the end-effector (mobile platform) is connected to the base (fixed platform) by at least two independent kinematic chains. Between the base and end-effector platforms are serial chains (called limbs or legs) [44].

A fully-parallel manipulator is a closed-loop mechanism with an n-DOF end-effector connected to the base by n independent kinematic chains, which have at most two links and they are actuated by a unique prismatic or rotary actuators [26].

Combinations of fully-parallel manipulator and additional serial axis are referred as hybrid systems.

A methodology for systematic design of different parallel kinematic machines topologies is proposed in [35] and it is presented in Fig.6.

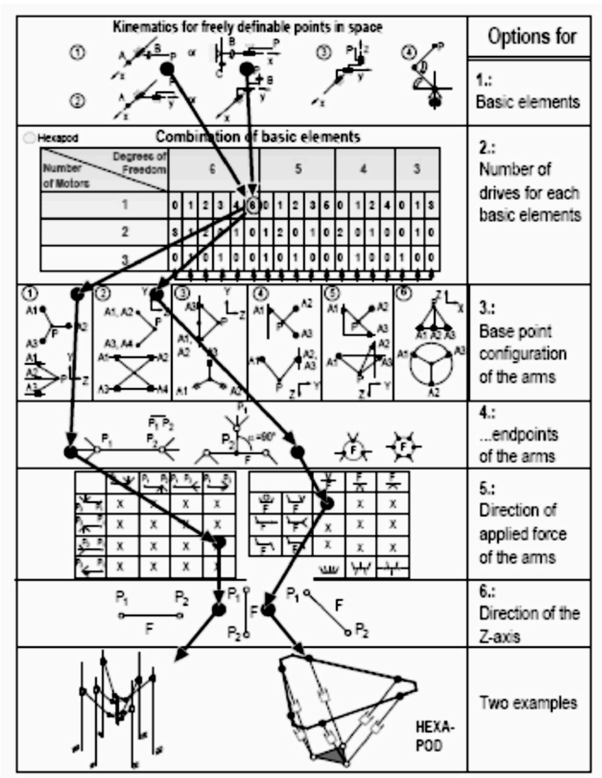


Fig.6 Methodology for systematic design of PKM [35]

The main idea is subdivision the mechanism into simple functional units. The kinematic substructures for the generation of the platform joint movements are chosen from a list of predefined solutions. A valid combination of these basic elements as well as the number of drives is then enumerated with respect to the required DOF of the end-effector. The geometric configuration of the joint connections is finally chosen from a list of predefined solutions.

Parallel manipulators can be classified according to their nature of motion in planar, spherical and spatial. The other classification is according the DOF of the end-effector [54].

We will illustrate the classification terminology on the well known example Gough platform (Fig. 3b). The end-effector is connected by six kinematic chains to the base, where each chain consists of a universal-joint (RR), a driven prismatic joint (P) and a spherical joint (S) at the moving platform (Fig. 7). In that case, the kinematic structure is denoted as 6-DOF-(RR)PS. To denote that some kinematic pair is actuated, the corresponding letter is underlined.

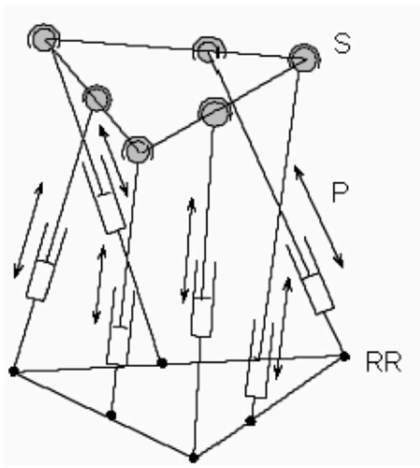
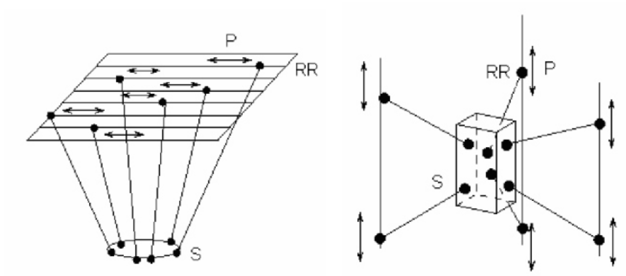


Fig.7 Gough Platform 6-DOF, 6-(RR)PS

The same end-effector movement can be realised with constant length legs but actuated foot points, for example Hexaglide [16] (Fig.8a) and Linapod [48] (Fig. 8 b) as 6-DOF 6-P(RR)S actuated with linear drives, or Hexa robot [34] (Fig.9) as 6-DOF 6-R(RR)S actuated with rotary drives.



a) b)

Fig. 8 Parallel manipulators 6-DOF 6-P(RR)S
a) Hexaglide b) Linapod

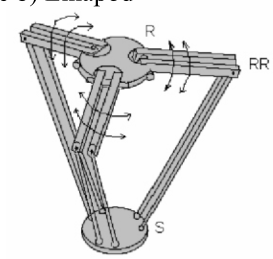
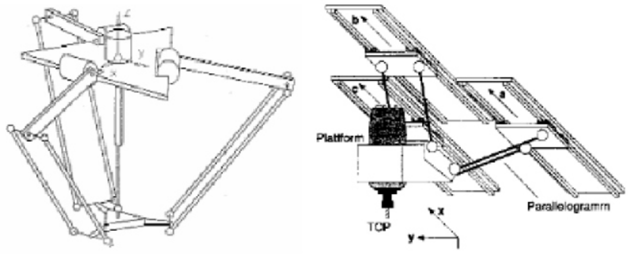


Fig. 9 Hexa robot 6-DOF 6-R(RR)S



a) b)

Fig. 10 a) Delta 3-DOF b) Triaglide 3-DOF

By grouping the individual chains into pairs with a common drive, three degrees of freedom can be locked, which results in parallel mechanisms with 3 DOF of the end-effector, examples are Delta robot (Fig.10 a) and Triaglide (Fig.10b)

4. Parallel kinematics machines advantages and disadvantages

Conceptual characteristics of the parallel kinematics machines were discussed in details in [38, 42, 46].

The Table 1 gives an overview of the advantages and disadvantages of parallel kinematics machines.

Table 1. Advantages and disadvantages of parallel kinematics machines

Advantages	Disadvantages
▪ High stiffness due to closed-loop kinematic chains	▪ Small and complex workspace
▪ Only compression and tension in the struts, no bending forces	▪ Low workspace/machine size ratio
▪ Small inertia	▪ Very complex control
▪ Very high dynamics performances due to the low moving mass	▪ Very susceptible to thermal loads
▪ High payload/ machine weight ratio	▪ Inherent danger of strut collision
▪ Many equal components	▪ Singularities in the workspace
▪ Possibility for modular design and reconfigurability	▪ Performance is pose dependent
▪ Position error-averages	▪ Complex key-components
▪ Linear drives used for rotary movements	▪ Complicated calibration
▪ Maximum force-summation of all actuator forces	▪ Force error-accumulates

5. Parallel kinematics machines characteristics

5.1. design of parallel kinematics machines (synthesis and optimal design)

One of the characteristics of the parallel kinematics machines is their nonlinear transmission of movements and forces from joint space to the end-effector space. These transmission characteristics are influenced by kinematic topology of mechanism and its geometric configuration.

It is well known that the performances that will be reached by any mechanism depend upon:

- the ***topology*** of the mechanism
- the ***dimensions*** of the components of the mechanism

This is especially true for closed-loop, parallel mechanisms that are ***highly sensitive*** to both factors. When we design a parallel kinematic machine (PKM) so that its performances should best fit to the list of requirements, both aspects must be taken into consideration:

- ***topological synthesis*** i.e. finding the general arrangements of joints, links that will describe the general kinematics of the structure.
- ***dimensional synthesis*** i.e. finding the appropriate dimensioning of the mechanism.

Synthesis of parallel manipulators is an open field (there are very limited number of papers deal-ing with this problem) [1, 5, 9, 25] and the main task for the development of parallel kinematic machines in practice.

The problems caused by using parallel structures in the field of machine-tool has shown that designers which have a deep understanding of open-loop mechanisms but, have not experience in closed-loop, are focused only on the development of the basic mechanical components of their machine and have almost completely neglected the analysis part.

Topology synthesis is a very complex problem for parallel mechanisms at the opposite of open-loop mechanisms for which the number of possible kinematic combinations is relatively reduced.

Parallel mechanisms, PKM, are highly sensitive to dimensioning. One classical example given in [27] is that by changing the radius of the platform of Stewart-Gough platform by 10% we may change the minimal stiffness over its workspace by 700% .

According [27] none of the existing dimensional synthesis methods are appropriate for parallel mechanisms which have usually a large number of design parameters. Furthermore these methods lead to a unique solution: in the case of parallel kinematic machines usually will not be a single solution to a design problem and providing only one design solution is not realistic. The main difficulty comes from the criterions which have to be considered: some of them are antagonistic (workspace and accuracy - a very accurate robot will usually have a small workspace and vice-versa), or not continuous (no singularity within the workspace), etc.

Therefore a design methodology should provide not only one single solution but, if possible, all the possible design solutions, or, at least, an approximation of the set of all design solutions.

With the optimal design (also includes topological synthesis and dimensional synthesis) which is crucial issue for development efficient PKM, several interesting problems could be solved, like optimization of:

-PKM kinematics (workspace, accuracy, maximal motion of the passive joints, dexterity, accessibility, motion pattern, kinematic error)

-PKM dynamic (PKM max acceleration, PKM max speed, inertia, centre of mass)

-PKM flexibility (PKM stiffness and PKM natural frequencies).

Optimal design is an open and actual problem. Very few papers could be found in this area [31, 32, 21, 22, 6, 12]. While tools and methodologies for performance analysis are already well established, the estimation of an optimal configuration for a given application has to be automated in order conceptual capabilities in terms of modularity and reconfigurability to be established.

5.2. Stiffness of parallel kinematics machines

The stiffness of the parallel kinematic machines is mainly influenced by the kinematics geometric synthesis and stiffness of the components. One of the targets during geometric synthesis should be homogenous transformation of forces from joint to end-effector space in order homogenous stiffness to be obtained all over the workspace.

The joints are key components of thePKM with respect to the stiffness.

Parallel kinematic machines require higher kinematic pairs with relatively large amplitude of motion, homogenous kinematic stiffness over their path of motion, and very often, capable to transfer relatively high load. Current available joints (either ball -and-socket or universal joints) are not completely satisfactory from this view point, although recent products like the INA joints have been developed especially for parallel kinematics machines [8]. Hence the development of higher kinematic pairs with 2 to 4 DOF is a key issue [2, 39]. As for any mechanical joints these joints must have a low friction, no hysteresis and must have a very reduced backlash. But in addition, these joints must be designed so that it is possible to add sensors to measure partly or totally the amplitude of the motion of the joints, which is important for the forward kinematics.

It is very difficult to give a general opinion about the stiffness of the recent parallel kinematic machines. On the other hand, it has been proven, that the conceptual advantage of PKM regarding stiffness can be implemented into real machines [14, 13]. On the other hand, geometric configuration and key-components are reason for inferior performance of PKM compared with serial kinematics machine tools [42].

When we compare PKM with serial kinematics machine tools, two things have to be considered. First the spindle/holder/tool system is the most critical element in the compliance between tool and workspace [42]. Thus, the inhomogeneous kinematic stiffness of the manipulator is decreased by the serial arrangement of machine and spindle/holder/tool system. Second, a nonlinear stiffness over the workspace can also be seen on many serial kinematics machine, for example fork heads, where stiffness depends on the orientation of the rotary axis.

Besides the static stiffness characteristics, the dynamic stiffness is of major importance for obtaining high chipload and drive dynamics such as adjustable velocity gain (Kv-factor) and jerk.

Comparing the frequency response function and modal analysis of different PKM, it can be observed that in general, vibrations of the legs are dominant but with low amplitude and phase shift, thus having low influence on the stability of the cutting process. On the other hand, vibrations in the legs can seriously affect the drive dynamics if they are coupled to the drive control [46].

5.3. Accuracy of parallel kinematics machines

Parallel kinematic machines theoretically should have high accuracy due to the closed kinematic loops and no error accumulating characteristics. Although more than 10 years passed since the first commercial kinematics machine tools were introduced, they are not widely accepted in the industry. From the beginning of their appearance it became obvious that the implementation of their theoretical capabilities in practice introduces many new problems. Accuracy of the parallel kinematics machine tools has became one of their main weaknesses.

But, what is different between theory and practice?

For the control and theoretical investigations generally a simplified model based on several assumptions is used. The assumptions are given in [45]:

- each joint has one centre point for all rotational degrees of freedom,

-these centres are precisely known,

-the linear actuators move with only one degree of freedom and pass exactly through the joint centres,

-the leg length can be read without errors, and

-no internal and external loads effect on the manipulator.

But these assumptions will easy fail for a real machine tool due to manufacturing and assembly errors, kinematic errors in the actuators and joints, elastic deformations due to the gravity, thermal deformations, limited sensor accuracy, control errors and others.

Similar to serial kinematic machine tools, as we mentioned before the accuracy of PKM is affected by many types of errors, which generally could be divided on static or quasi-static and dynamic errors. Static errors and quasi-static are errors not dependent on the dynamics and process forces, whereas the source of dynamic errors, is in the machining method. Overview of the most dominant errors which have a greatest influence on the parallel kinematics machine tools accuracy, is given in Table 2.

Table 2. Types of errors at the PKM

STATIC AND QUASI-STATIC ERRORS	DYNAMIC ERRORS
▪ Kinematic errors	▪ Errors from elastic deformations
▪ Transformation errors	▪ Errors from natural vibrations
▪ Gravitational errors	▪ Drive errors
▪ Thermal errors	

Due to the parallel structure, the errors of the individual axis are coupled, for example a single axis error will cause errors in all DOF of the end-effector. Thus, the error sources are more complex to separate than in serial machines, where the individual axis are calibrated one by one [33].

To achieve the required accuracy, the transformation model in the controller has to fit to the real machine behaviour. Usually, fitting the transformation model is done by calibration and compensation.

Different strategies can be used:

First strategy. The geometric parameters used in the transformation model are identified by calibration. The main difference between the calibration of parallel kinematic machines and the calibration of serial kinematic machines lies in the very high number of geometric parameters at parallel kinematic machines.

The method for calibration of parallel kinematics machines consists of measuring the position and orientation of the tool centre point at several points in the workspace. Afterwards, the geometric parameters of the kinematics are determined by a numerical optimization.

The accuracy achieved with this optimization depends on various factors Measuring method used for determining the position of tool centre point during the calibration plays an important role. Because of nonlinear coupling of all parameters a one -dimensional measurement, as for example, x component of the tool position or the distance between tool tip and fixed point, could be enough. But if we know the positions and orientations of the tool centre point in the measuring points, a higher accuracy will be achieved by calibration.

Another important factor is the number of measuring points and requirement the measuring points to be spread over the whole workspace. The more measuring points are used, the real geometric parameters can be better determined by averaging.

There are two types of calibration methods:

• ***external***: an external measurement device is used to determine (completely or partially) what is the real position of the tool centre point for different desired positions of the tool centre point. The differences between the measured position and the desired position give an error signal that is used for the calibration.

• ***self-calibration***: the PKM has extra sensors which are used for the calibration [18].

The first method is difficult and tedious to use in practice, but usually gives good results. The second method is less accurate, but is easy to use and has also the advantage that it can be fully automated.

The measurements generally can be in one DOF, for example with a double-ball-bar [45, 24] in three DOF, for example with a laser tracker [40] or double -ball-bar triangulation [47], as well as in six DOF with a special device based on induction sensors and level-meters [28].

Second strategy. Spatial error compensation by means of a three dimensional matrix of measured errors over the workspace, which are compensated within the controller [40].

Third strategy. Functional compensation of the predictable errors, for example sagging due to the gravity forces. The leg forces are calculated [45] or established by the motor current in controller [40]. The resulting deformation of the kinematic chains then is compensated.

Within the actual realised PKM, in general a combination of the above listed strategies is used.

The most effective measure against thermal errors is the cooling of thermally effective kinematics components [45].

Another possibility to reduce errors caused by thermal deformations is the temperature measurement of the components and the compensation of the resulting deformation using a thermal model. Because of the limited accuracy of the thermal model and high number of the needed temperature sensors, this procedure is restricted in regard to the achievable machine accuracy, especially since the thermal model for the parallel kinematics machine tools is very complex [19].

According [46] the reported positioning errors in Cartesian axis for some 5-axis PKM are in range 10-20 μm, and for some 3 axis PKM are between 10 and 15 μm.

But generally most of the PKM reach today about 20-50 μm working accuracy [43].

5.4. Motion control of parallel kinematics machines

Parallel kinematics machines in general are programmed in Cartesian space similar to conventional serial link machines. The transformation from Cartesian space to joint space is computed in the controller at least each interpolation cycle. In recent parallel kinematic machines in general (more than 70%) commercial control systems are used. [46]. The specific transformation functions are either implemented on external processor boards or directly within the NC unit via original manufacturer interfaces. For safe and efficient machine use the controller has to have additional functions, such as look-ahead function in joint space and monitoring of the workspace limits of the parallel manipulator [16, 17], as well as accuracy related functions as error compensation and a support for the calibration of the machine [40, 45, 28].

The drive control of parallel kinematic machines is usually realized in joint space by independent axis controllers designed similar to the classical serial machines as cascaded P/PI controller. It has been observed, that on higher velocities, tracking errors increase drastically [17], and in that case the velocity should be limited in favour of better path accuracy [15]. These limitations are induced by inherent nonlinear behaviour of PKMs such as variable inertia and coupling effects of the individual drive. Limited resolution of the velocity feedback, calculated by the time discrete differentiation from the actual position feedback is identified as limitation factor for the control parameters of linear direct drives [36]. By integrating additional Ferraris sensor in the acceleration feedback, a higher quality velocity feedback is obtained which enables higher control parameters and increased tracking bandwidth and disturbance rejection behaviour [37].

Other approaches incorporate the nonlinear behaviour of the parallel manipulators in control laws [16, 36,11]. It is shown in [17, 11, 7] that the tracking errors can be greatly reduced by applying model control scheme, that computes the actuator torques or forces for a given trajectory. The feedback controllers then only need to correct unmodelled effects, for example friction. The parameters for the dynamic model can be identified and optimised online by the controller with adaptation algorithms.

Nonlinear control strategies require high computational efforts for the calculation of the dynamic properties and fast interfaces to the drive controller. That is reason, why their implementation into commercial machine tool controllers is still open issue.

5.5. Realised parallel kinematics machines

In the last more than 10 years about 50 different PKM structures are realised. Overview of their technical characteristics and manufacturers/laboratories for most of them, can be found in [46, 51, 54, 55]. More than 80 % of the realised parallel kinematics machines are machining centers for 3-axis or 5-axis milling processes. Recently other types of PKM for turning, forming and riveting were established.

5.5.1. 3-Axis milling parallel kinematics machines

Currently several machine tools manufacturers are investigating the capabilities of PKM for high speed 3-axis machining centers at pilot customers and some manufactures are ready to start or already star-ted with serial production. In the following several examples of the 3-axis PKM will be given:

SKM 400 In 2000, StarragHeckert (formerly Heckert Werkzeugmaschinen GmbH) launched a new, pioneering technology with the SKM 400 Kine-matic machining center based on the idea of repla-cing the linear guideways by revolving joints. Star-ragHeckert has developed a patented variant for a tripod (Fig.11)

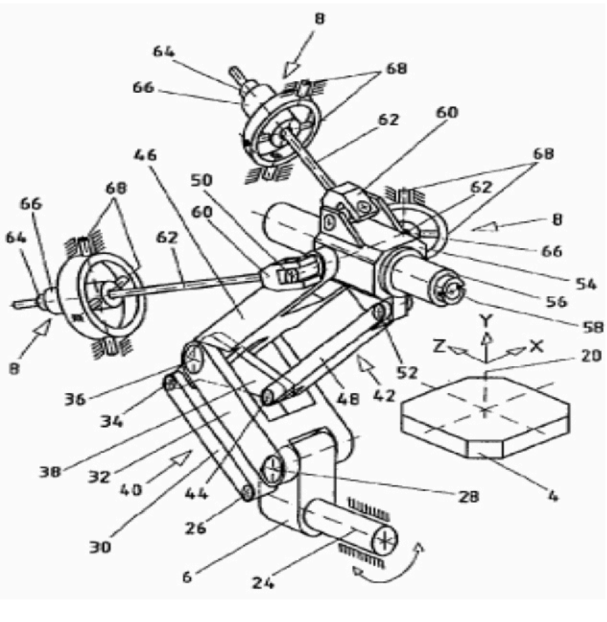
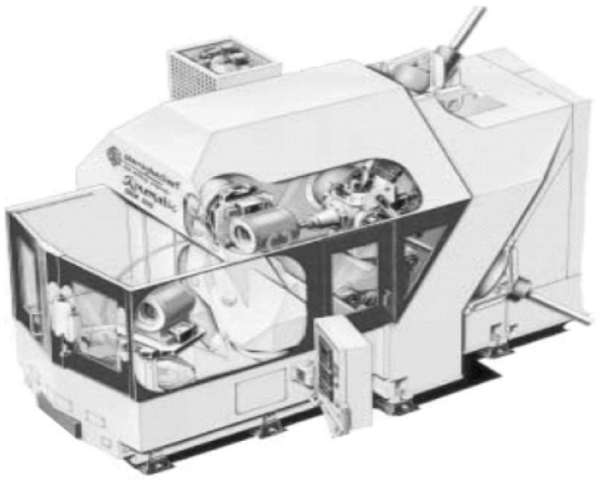


Fig 11 Patent No.:**WO 00/09285 A2**
Title: **Machine-Tool, Especially Milling Center**
Inventor(s): Achim Pönisch Applicant(s): Heckert Werkzeugmaschinen GmbH Issued/Filed: February 24, 2000 / July 28, 1999 Note: **SKM 400 a 3-DOF PKM** [49]

The SKM 400 (Fig. 12) is realised as fully parallel system based on three extensible legs which are linked by universal joints both at the platform and the machine frame. The spindle carrier is supported by an additional passive chain, to look the rotational DOF. The workspindle is always moved horizontally in the space via coupled kinematics. The workspindle carries out all translatory displacements in the longitudinal, transverse and vertical axes only together with the tool. The machine is free of column, bed, slide, slide rest, guideways and their covers.

The machine is characterised with good relation between workspace and required floor-space which is similar to conventional serial machines [40]. Its serial production has already started.

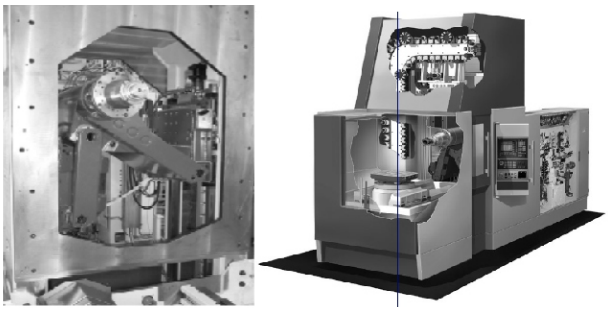


Workpiece holder/punched pallet DIN 55201		
NC rotary table without pallet changer		
Clamping area	mm	400×400
Input and display resolution	deg	0.001
Max. load	kp	1000
Max. speed	rpm	100
Interference diameter*	mm	700
NC rotary table with pallet changer (option)		
Clamping area	mm	500×500 (630×500)
Input and display resolution	deg	0.001
Max. load	kp	500
Max. speed	rpm	25
Interference diameter*	mm	700
Number of pallets		2
Pallet change time	s	9
Number of load-unload stations		1
NC rotary/swing table with pallet changer (option)		
Clamping area	mm	500×500 (630×500)
Input and display resolution	deg	0.001
Max. load	kp	500
Max. speed	rpm	100
Interference diameter	mm	700
Number of pallets		2
Pallet change time	s	10
Number of load-unload stations		2
Workspindle travel		
Longitudinal motion/x axis	mm	650
Vertical motion/y axis	mm	650
Transverse motion /z axis	mm	650
Workspindle/motor spindle		
Drive power at 100% c.d.f.	kW	19
Drive power at 40 % c.d.f.	kW	31
Torque at 100 % c.d.f.	Nm	165
Torque at 40 % c.d.f.	Nm	200
HSK-A63 toolholder		HSK-A63
Speed range	rpm	50...15,000
Automatic tool changer/ chain magazine		
Magazine locations		60

Max. tool diameter	mm	160
Max. tool length	mm	350
Max. tool weight	kg	10
Max. breakdown torque	Nm	10
Machining time	s	3.5
Axis module traversing rate		
Feedrate range	m/min	0…100
Feedrate force/axis module	kN	10
Rapid traverse rate	m/min	100
Acceleration	m/s²	10
Coolant system		
Supply through spindle center		
Delivery rate	l/min	30/27/24
Pressure	bar	30/40/50
Supply via nozzles		
Delivery rate	l/min	50
Pressure	bar	2
CNC		Sinumerik 840D

Fig.12 Parallel kinematic machining center SKM 400 and its technical data (Source Starragheckert)

GENIUS 500 The Specht Xperimental (from 2004 in serial production with name GENIUS 500) (Fig. 13) is hybrid system where the x-y movements are realised by a parallel scissors kinematics whereas the z-axis is located in the table. The x- and y-axis with patented coupler (scissors) kinematics (Fig.14) powered by linear motor drives allow the accelerations 15-24 m/ and feed rate 120-180 m/min combined with rigidity bigger than 30 N/µm.



Technical Data
Work area (X/Y/Z): 630 mm / 630 (max. 1040, if X=0) mm / 1000 mm
Max. rapid traverse rate X/Y: 120-180 m/min
Max. rapid traverse rate Z: 75 m/min
Max. acceleration X/Y: 15-24 m/
Max. acceleration Z: 10 m/
Radial Rigidity: > 30 N/µm
Jerk X/Y: up to 1200 m/
Main spindle: HSK-A 63, 16000 min-1, 43 Nm at 100% ED
Option: Spindle with higher torque
Option: Minimum quantity lubrication
Magazine capacity tool: 57 places
Max. tool weight: 10 kg
Max. tool length: 600 mm
Max. tool diameter: without empty positions: 95 mm with empty positions: 230 mm
Chip to chip time: 2,5 s (with 2 x 4 kg)
Tool change time: 0,8 s (with 2 x 4 kg)
Clamping surface on rotary table: ø 600 mm
Transport load: 800 kg
Fixture envelope: ø 800
Fixture height: 1050 mm
Controls: Siemens 840D or Bosch Rexroth MTX
Machine dimensions (LxWxH): 6700 x 2050 x 3780 cm

Fig.13 Parallel kinematic machining center GENIUS 500 and its technical data (Source: Cross Hüller)

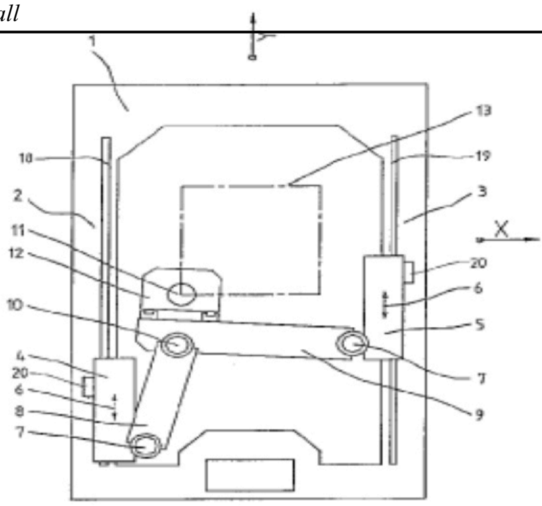


Fig.14 Patent No.: **US 6328510** Title: **Machine tool for three axial machining of work pieces**
Inventor(s): Hanrath et al. Applicant(s): Huller Hille GmbH Issued: 2001-12 Note: **GENIUS 500 (Cross Hüler SPECHT Xperimental) a 3-DOF PKM** [49]

5.5.2. 5-Axis milling parallel kinematics machines

Many machine concepts based on parallel kinematics have been realised for 5-axis machining. While in the past fully parallel concepts were dominant, recently we can observe trend towards hybrid structures. In the following we will present several parallel kinematics machine tools intended for 5-axis machining.

COSMO CENTAR OKUMA PM600 Okuma's Cosmo Center PM-600 (Fig. 15 and Fig.16) is fully parallel mechanism machine tool developed to achieve high-efficiency production of aluminum parts and dies and molds that requires less polishing work and integrates operations for cutting complicated shapes. According to Okuma, it offers high-speed machining, sculptured surface machining and continuous operation.

The machine is capable of machining speeds to 100 m/min and 1.5 G acceleration. Spindle tilt angle is max ±30°. Each of the machine's six ball screws is integrated with a hollow servomotor and a hollow rotary encoder. Universal joints use a combination of pre-tensioned roller bearings. Other features include: table 750 x 750 mm, workspace: 420×420 ×400 mm (a cylinder of 400 mm height and 600 mm diameter), travels X-Y × Z / spindle tilt 800 × 400 / 0° mm, spindle speed 50 - 12,000/30,000 min^{-1}, motor (few minutes/cont) 9 / 6 kW, floor space 2405× 2830 mm. The automatic tool changer can handle up to 20 tools.

It is really a six-axis machine, based on a standard Gough-Stewart platform architecture, but it is used for five-axis machining That machine can also be programmed for three-axis milling, keeping the head stationary in the vertical plane.

Fig. 15 Parallel mechanism machine tool COSMO CENTER PM-600 [53]

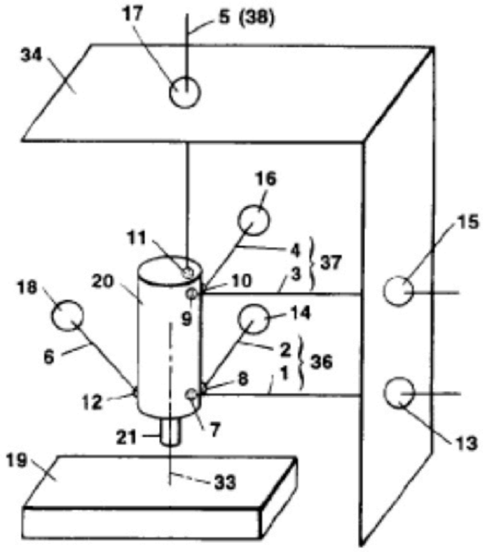


Fig. 16 Patent No.: <u>**US 6,203,254**</u> Title: **Parallel Mechanism Machining Device** Inventor(s): Masayuki Nashiki, Tetsuya Matsushita, Masao Nakagawa, and Shigeharu Watanabe Applicant(s): Okuma Corporation Issued/Filed: March 20, 2001 / September 30, 1999 Note: **Cosmo Center PM-600 a 6-DOF PKM** [49]

MACHINING CENTRE LINES ECOSPEED AND ECOLINER

The 5 axis machining centre lines ECOSPEED and ECOLINER from <u>Dörries Scharmann Technologie GmbH</u> are hybrid structures equipped with the Sprint Z3 tool head. Machining centre lines ECOSPEED and ECOLINER are designed for high speed machining of large aluminium structural components (ECOSPEED, ECOSPEED F and ECOLINER) and for production of small to medium sized components, focused on applications in the: aerospace industry, automotive industry and tool and die industry (ECOSPEED F HT) (Fig.17).

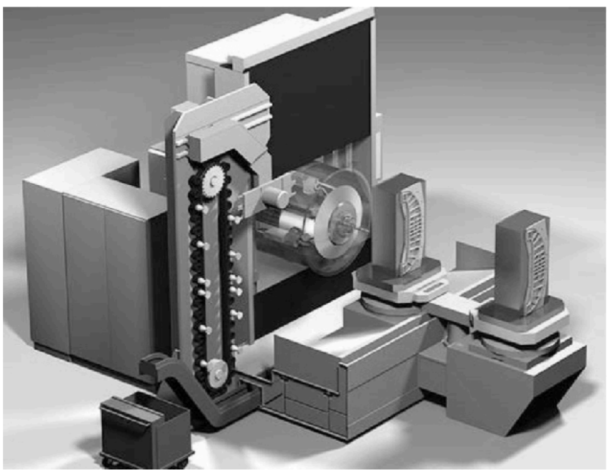


Fig 17 ECOSPEED F HT 5-axis machining center with parallel kinematic machining head Sprint Z3 [50]

The machining centers are realised as a hybrid systems with Sprint Z3 3-axis fully parallel kinematics tool head (Fig. 18) that may move in Z and tilt in all directions, and which is carried by serial X and Y axis as cross slide.

Sprint Z3 head, it's a horizontal parallel linked tripod that uses three parallel linear ways and ball screws attached by linkage to a spindle carrier. The unit is designed to achieve virtually any combination of linear and rotary motion within the head's working zone. Three parallel horizontal legs (Fig.18), all attached at one end to a spindle housing. Each of the legs attaches to the housing at 120 degrees around the periphery using a ball joint so the housing can pivot. The other ends of the legs attach via a joint to a block that travels in the plus and minus Z-axis direction carried on a fixed set of parallel linear guide ways. There is an atached ball nut under the bloc through which a balls crew spins. Each of the three ball screws is powered by its own servomotor. As each of the three ball screws spins, its respective block moves the spindle housing. When all three balls crews are actuated in unison, the spindle housing moves in a straight, plus or minus, Z-axis direction. Program the ball screws to move independently, and the carrier, with its spindle, can create A and B axes of motions. Range for these motions is 40 degrees plus or minus about the A or B axes. The triangulation setup using parallel links gives the spindle high stiffness characteristics in both dynamic and static modes. Because of the reduced mass of the design, axial acceleration and deceleration for the Z3 head is 1G. Rapid feed rates are up to 50 m/min. The Z3 head's maximal Z-axis travel has been limited to 670 mm. This limited stroke gives the head rigidity to better machine thin wall sections in aluminium aerospace structural components.

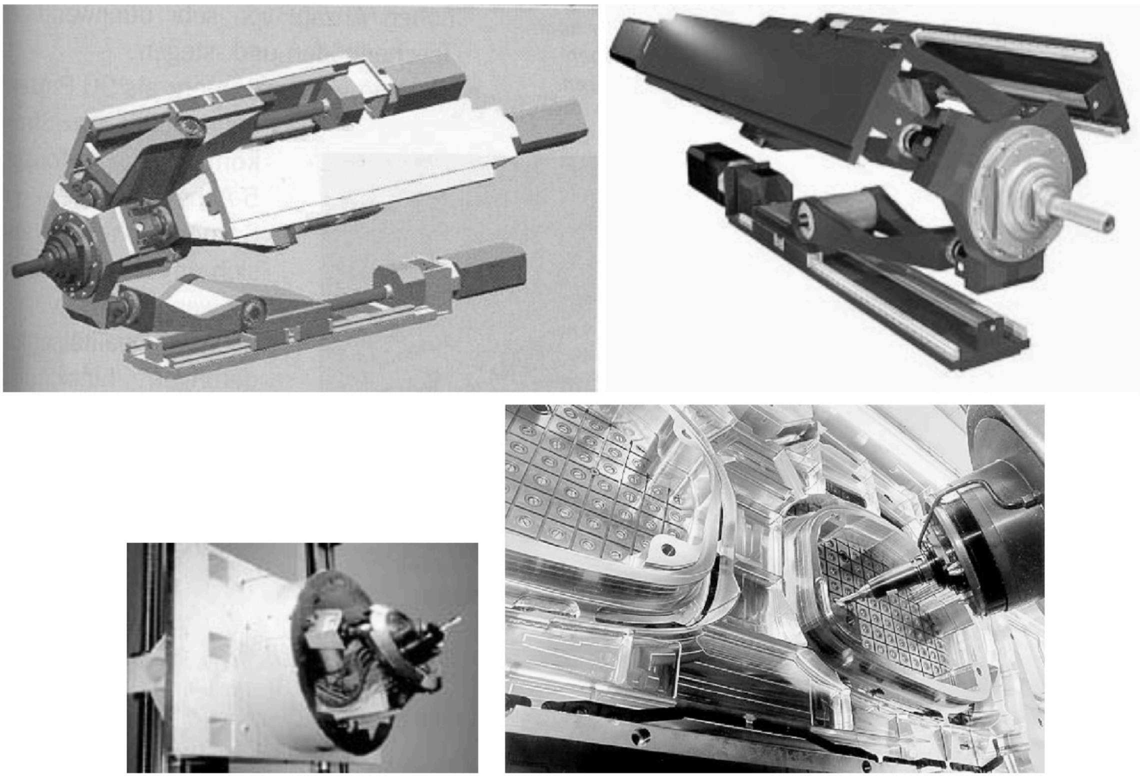


Fig. 18 Sprint Z3 parallel kinematic tool head [50]

The new Z3 head accommodates a motorized spindle with speed ranges of 7,500 to 40,000 available. Spindles up to 80 KW can be accommodated by the Z3 head design. Three different spindle brands are being offered for use in the Z3 to give users a choice of speed and torque combinations for various machining applications. Other characteristics of the Z3 head are: rotary acceleration - 685°/s^2 , rotary positioning velocity - 80°/s.

More than 20 ECOSPEED's machining centers are already in use in aircraft industry.

DECKEL MAHO Pfronten TRICENTER DMT100

DECKEL MAHO Pfronten TriCenter DMT100 is 5-axis hybrid structure milling machine (tripod with length-variable struts plus serial 2-axis milling head) (Fig.19). TriCenter is specially focused on tool dexterity. The rotary axis are realised as a serial fork head. Based on the kinematics of the Tricept (Fig.5), the TriCenter is a complete redesign to improve machine rigidity and patented (Fig.20). A pre-series prototype was shown on EMO 2001 fair.

The machine uses three actuators to move a central tube on which rides a specially designed two -axis serial milling head. The setup can cover the machine's 1500 X 800 X 700-mm work cube with rapid traverse rates to 100 m/min and acceleration of 2 G. With a positioning range of 120º in the *A* axis and 180º in *C*, the design allows single-setup machining of all types of complex workpieces. The drive system consists of ball screw drives, INA -struts. The control system is Siemens 840 D. The target application is aircraft industry and this machine allows high removal rates in aluminium alloys and steel. A serial production is expected very soon.

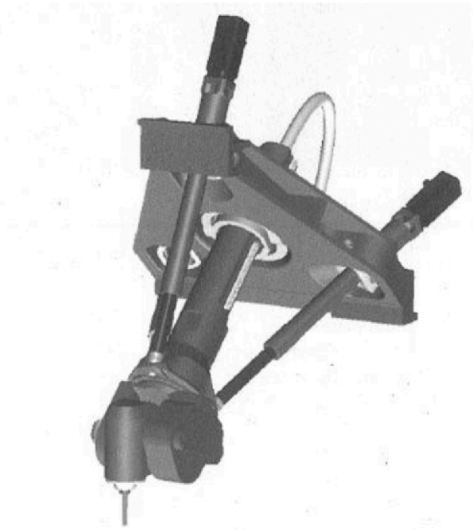


Fig. 19 DECKEL MAHO TriCenter DMT100 5-axis hybrid machining [51]

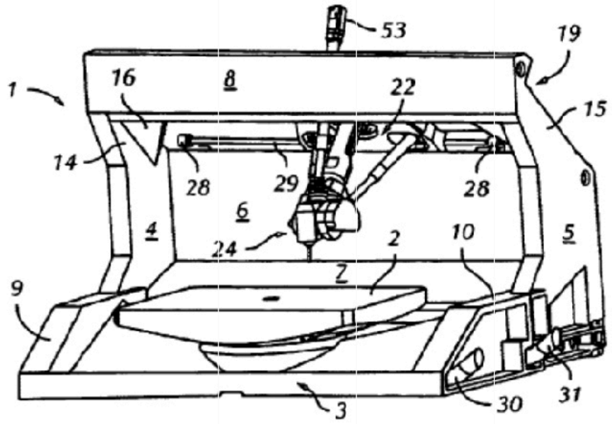


Fig. 20 Patent No.: **<u>US6682278</u>** Title: **<u>Universal combined milling and boring machine</u>**
Inventor(s):Gronbach; Hans Applicant(s): Deckel Maho Pfronten GmbH Issued: 2004-01-27 Note: **Tri Center-Deckel Macho Tricept** [49]

TRICEPT HYBRID 5-AXIS PKM.

SMT Tricept (SMT Tricept from 2004 is a part of PKMTricept Company from Spain) is a company that has been in the PKM metal cutting machine business for a relatively long time-since 1994. It produces three types of Tricept PKM machines (Fig. 21) (5-axis hybrid structure-tripod with length variable struts plus serial 2-axis head) for metal cutting and other applications.

The largest, the Tricept 845 is equipped with a unique and patented **Direct Measuring System (DMS)**. This system is based on a combination of the Tricept standard parallel kinematics positioning system and the traditional Cartesian positioning system mounted on the centre-tube and its suspension. These two systems compare the X-Y-Z positioning values during operation in real time. DMS increases the stiffness and accuracy and it also compensates against the effects of cutting forces and temperature changes.

A **Wrist Measuring System (WMS)** controls the actual position of the rotary axes by means of external encoders mounted directly on the moving parts of the A and C axes.

A machine stand design based on a **Modular Element System (MES)** provides for flexibility to configure the machine to different angles (0°, 45°, 90°) and reconfiguration on site.

The **Modular Setup System (MSS)** offers easy and economical means of altering the set up when a customer wishes to change process/applications for the machine. A series of exchangeable modules are available.

Applications vary from light to heavier five axis machining of aluminium and plastics parts, model making, tool and die machining, etc.

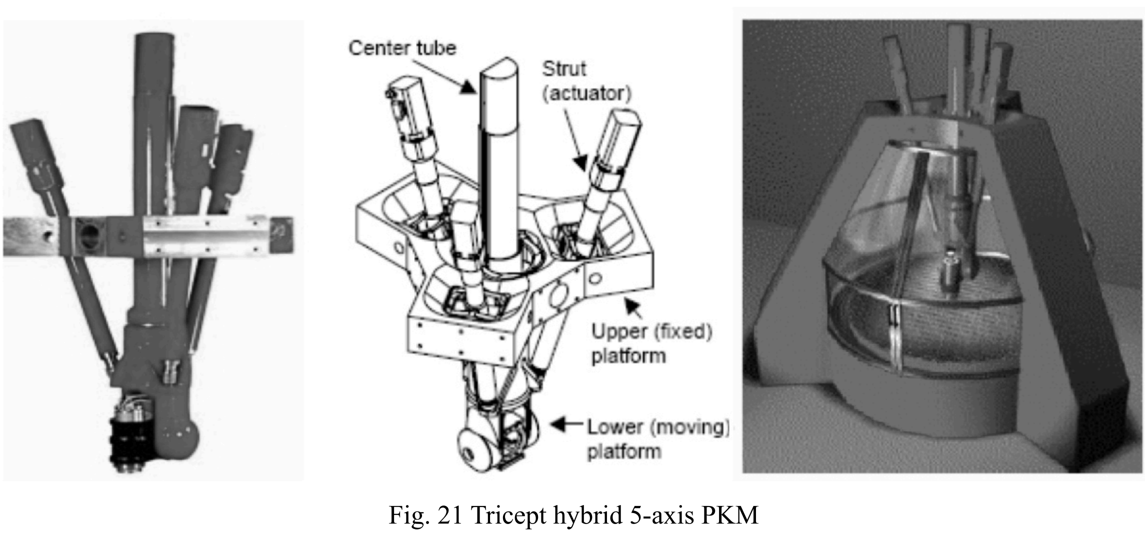


Fig. 21 Tricept hybrid 5-axis PKM

In the following are given some of the technical characteristics for Tricept TMC 845: volumetric accuracy ±50μm; repeatability ±10μm; max feed rate 90 m/min; max acceleration 2G; Direct Measuring System (DMS): Heidenhain high resolution encoders; Wrist Measuring System (WMS): Heidenhain high resolution encoders; control system: Siemens SINUMERIK 840D; spindle 30/45 KW, 24,000 - 30,000 min$^{-1,}$ HSK 63 ; tool changer: rack type,13 tools; umbrella type, 24 tools; floor space (machine) 3.7x3.6 m; floor space (incl. control cabinet and chip conveyor) 7.1x5.8 m; total machine weight 30,000 kg.

More than 200 machines are sold, mainly to automotive and aerospace customers such as GM, BMW, Peugeot, Citroën, Boeing, Airbus, Volvo, Scania, SAAB Aerospace, Renault, Volkswagen, Alstom.

5.5.3. Non milling applications of parallel kinematics machines

Recently parallel kinematics machines start to focus on other applications than milling, for example turning, riveting, forming as well as wood working.

VERTICAL TURNING MACHINE INDEX V100

In order to reduce the non-productive time for the high volume production the company INDEX-Wer-ke developed a vertical turning machine V100 (Fig.22) based on linear delta kinematics. The spindle unit is capable of 3-axis movements, which enables feeding motion for machining and part handling. Mainly is intended for turning application , but also milling, grinding, laser hardening, laser welding, assembling operation can be performed with optional available driven tools.

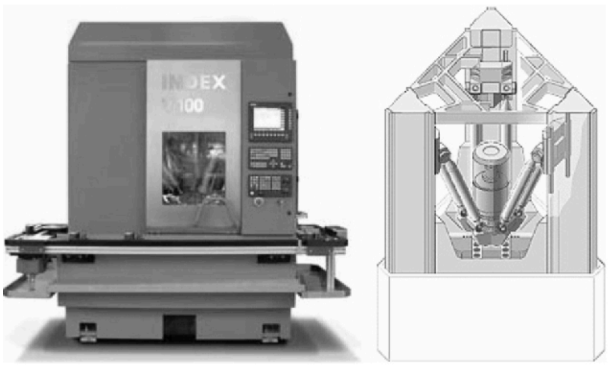


Fig 22 Vertical parallel kinematic turning machine V100 [52]

In the following some of the technical characteristics for the parallel kinematic turning machine INDEX-Werke V100 are given: workspace: 250×250×150 mm; max. traverse rate: 60 m/min; max. acceleration: 1 G; work-spindle: max. speed 10000 min^{-1} ; power at 100% 10,5 KW; torque at 100% 50 Nm; chuck size max. 130 mm; tooling system: cylindrical shank DIN 69880-25 / 69880-30, max. 16 tool stations; dimensions L x W x H 2100 x 2100 x 2300 mm.

6. Parallel kinematics machines in practice

Predestined ranges of parallel kinematic machines application could be clarified for the following domains: tool and die making, power train, aircraft construction and flexible forming technologies.

If we would like to list the successful practical applications of parallel kinematic machines in serial production in the last 10 years of research and development made efforts, we would come to a disappointing result [43].

Actually, we could list 3 successful examples:

- Tricept for deburring, milling and drilling (not too precise) of simple automotive parts,
- ECOSPEED Machining centers for milling and drilling of alloy integral aerospace parts
- Index V100 for turning and additional operations of turned parts.

After we analyze the benefits of each concept, we can find 3 common reasons for success:

- the right design concept adapted to the specific application,
- to use the benefit of the specific PKM advantage(s) in application
- to avoid the disadvantages, using consequently their strong points according the rule “only as good as necessary”.

Here the examples:

- high speed/low precision deburring,milling and drilling-Tricept is sufficient;
- solving the current bottleneck in 5-axis high speed machining, the limited dynamics of a rotary tool axis and the required compensation movements of the linear axis- Special
- Z3 Sprint parallel kinematic head implemented in ECOSPEED Machining centers;
- a vertical turning machine based on linear Delta principle with a limited working area for (high) precision turning application and an expanded working area for others (not high stiffness required applications) as measuring, handling load and unload- INDEX V 100 is optimal.

The common issues for the above mentioned 3 machine concepts are: limited universality, devoted to specific technological applications (technology and workpiece) and high performance machining as a consequence.

For the future more successful introduction of PKM in practice, we should be focused on two main targets:

- characteristics of the parallel kinematic machines should be comparable with serial kinematic machines and

- parallel kinematic machines should not complicate operator's life more than serial kinematics machines.

7. Conclusion and recommendations for future

Parallel kinematic machine tools after more than 10 years intensive research and development efforts, slowly but surely, entering the commercial market in different industrial applications enables benefits to the customers.

The parallel kinematic machine tools which are successful on the market have been designed to solve some specific problem (bottleneck) in the application of serial machine tools, and to enable most effective use of conceptual advantages of PKM, and in the same time avoiding the conceptual disadvantages by conceptual approach or advanced technological solutions.

If we compare about 10 years research in parallel kinematic machine tools and more than 200 years experience and research to reach the current level of serial machine tools, it is easy to conclude that solving the problems in PKM will need time.

In order to obtain wider practical application of parallel kinematic machine tools the further intensive research and development is necessary.

We will mentioned here several open problems and needs:

- in the field of design and performance prediction of parallel kinematics machine tools it is very important effective tools for optimal topological and dimensional synthesis and overall design of the PKM towards special application to be created in order the most effective use of conceptual advantages of the parallel mechanisms to be possible;

- parallel kinematics machine tools consist of components like joints and struts which have key importance of the overall performance characteristics of the machine. Further improvement and refinement of components is needed;

  For example, creating joints with high and linear stiffness, high damping and wide swivelling angles; development of components fitted to special kinematic structure; lightweight construction of assemblies subjected to torque, etc.;

- accuracy and controller. Analysis have shown that more of the 70% errors on the fabricated parts are induced by the controller, CAD/CAM system is responsible of approximately 20% of the errors, and the parallel mechanism (if optimally designed) less than 10% [26]. Hence, research should be focused mostly on the controller. The hardware of the controller should support: the possibility of using appropriate control laws capable to deal with inherent nonlinearities of parallel kinematic machine tools; parallel computation (that will drastically improve the sampling time); creating automated calibration algorithms and routines for high position accuracy to be realised; generating interfaces for the compensation models (elastic and thermal deformations in the controller; active compensation of the disturbance forces, etc.;

- maintenance issues, like machine calibration and evaluation of geometric accuracy should be practically, shop-floor, developed and oriented. This would enable the machine users to handle these issues according their previous experience with classical serial machine tools.

8. Acknowledgments

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АЛАТНИ МАШИНИ СО ПАРАЛЕЛНА КИНЕМАТИКА: ИСТОРИЈА, СЕГАШНОСТ, ИДНИНА

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Апстракт: Пред извесно време алатните машини со паралелна кинематика го привлекоа вниманието со своите карактеристики: голем динамички потенцијал при движење, прецизност и крутост заради затворената кинематска структура и не акумулирање на грешките. Овој труд дава преглед на развојот на алатните машини со паралелна кинематика, нивните карактеристики и нивната практична примена споредена со алатните машини со сериска кинематика.

Клучни зборови: алатни машини со паралелна кинематика, карактеристики, примена

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GAS-SHIELDED METAL ARC BRAZING OF ZINC COATED STEEL SHEETS

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Abstract: The paper shows part of the results given from the investigation of brazing of zinc coated steel sheets by low energy ChopArc process. Zinc coated steel sheets with thickness of 0,75mm (Zn 54g/m^2) brazed edge joining in horizontal position with filler material CuAl5Ni2 in a shape of wire and diammeter 0,8mm in a shielding gas mix 98% Ar+2% CO_2. The quality of brazed joints was established with metalogrphic examinations. The structure of the e-brazed joints and the basic material was also analized. Measurement of the microhardness by Vicker's method and tensile tests of the brazed joints was effected.

Keywords: zinc coated steel sheets; gas-shielded metal arc brazing; ChopArc process; microstructure analysis; tensile strenght.

1. Introduction

There is much wider use of zinc coated steel sheets recently in the production of automobiles, households and food industry as well as in transport industry, building and architecture.

The reason for galvanizing or putting of a zinc coat with thickness of 1 to 30μm is to increase the corrosion resistance of the surface and for better visual appearance.

The joining of zinc coated elements is very difficult when conventional arc methods of welding are beeing used. The basic problem during the welding is the low melting temperature (420°C) and the zinc evaporation (906°C). Zinc steam gets intro the arc and in great deal disturbs its stable burning. Unstable arc causes porosity and cracks in the joint, and dispersion of the melted filler material in the surrounding. The obtained joints have very bad quality and need additional treatment.

A successful joining of the zinc coated elements is effected by arc brazing methods: one of the most applied method is gas-shielded metal arc brazing (GSMA or MIG/MAG), the ones that are less applied are gas-shielded tungsten arc brazing (GSTA or TIG) and plazma arc brazing [1, 2].

2. Gas-shielded metal arc brazing

GSMA brazing is widely applied because of the inovations in electronics, which is a base for invent-ion of new welding and brazing devices with pulse current. These brazing devices have horisontal constant voltage characteristic, but the electric arc burns with impuls current and its stable burning is supported even during very low currents, which is very difficult to be realised with the conventional welding devices [3,4].

The transfer of the melted filler material is in cycle of one melted drop for one impulse.The shape of the impulse depends on the type of the filler material,the braze and the type of the shielding gas. Figure 1 shows an impulse of a simple shape. In order to decrease the quantity of the input het energy an to mini-mize the melting of the material the shape of the impulses is constantly improving. One of the most improved shapes is during the Chop-Arc process which is discussed in heading 3.

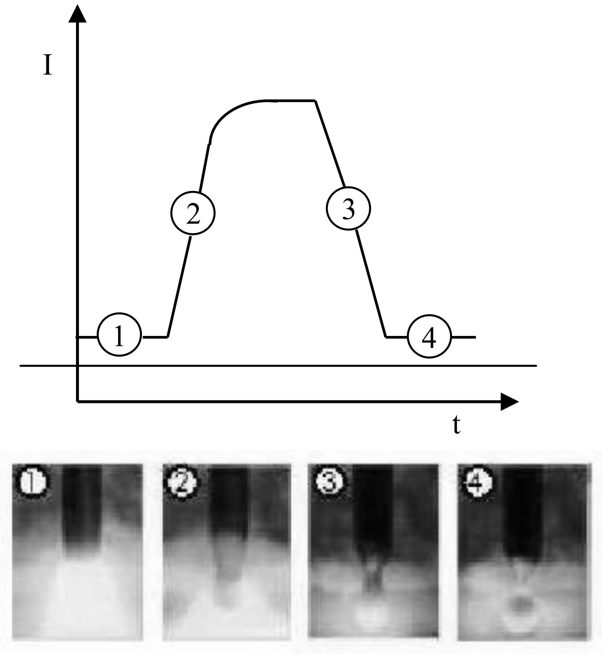


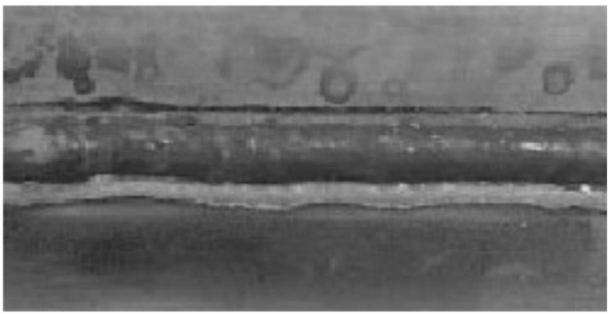
Fig. 1. Pulsed deposition of melted filler material

During this process, the input of heat compeared to the GSMA welding is ten times less, at the same quality of melted material. That is why these methods are known as lowenergy methods of joining.

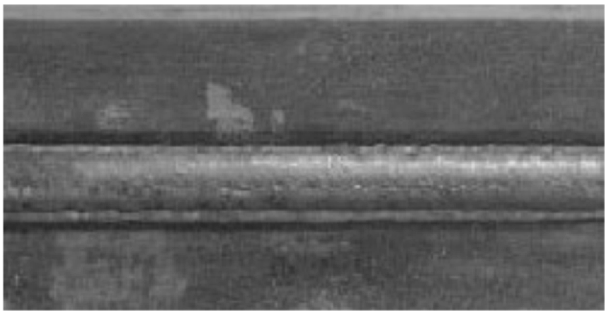
Because of the little input of heat, very small part of the zinc coated layer is melting and vaporating. Part of the melted zinc makes bond with the melted filler material, which is most frequently alloy CuSi3, CuAl8 or CuA15Ni2, and the brazed joint becomes corrosion resistance.

The small quantity of the vaporated zinc has no impact on the stability of the arc, which is with a small length, and the result is weld without splatter and porosity in the joint.

The structure of the shielding gas surrounding has an impact on the quality of the brazed joint specially on the splater of the melted material. If the shielding gas is pure argon (Ar), the joint has a bad quality, splater occurres (Fig. 2a). But with addition of O_2 or CO_2 to 2%, the stability of the arc is improved, which leads to smaller splater of the melted metal (Fig. 2b) [5].



a. Shielding gas Ar



b. Shielding gas Ar +1%O_2

Fig. 2 Impact of the shielding gas surrounding upon the look of the joint.

Zinc coated elements of different positions and joints can be sucessfuly joined by GSMA brazing (Fig. 3), whether it is done manualy, automatically or by robot.

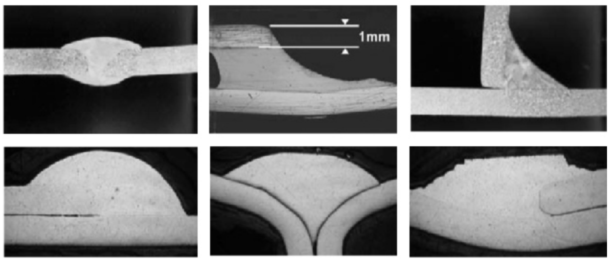


Fig. 3 Types of GSMA brazed joints

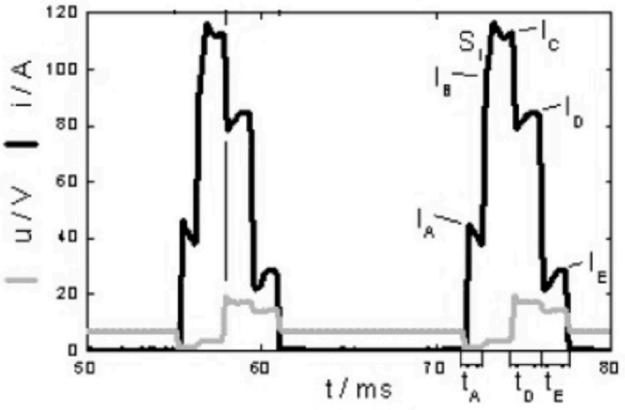
The main and largest use of GSM brazing is in the production of car bodies (Fig.4) [6].

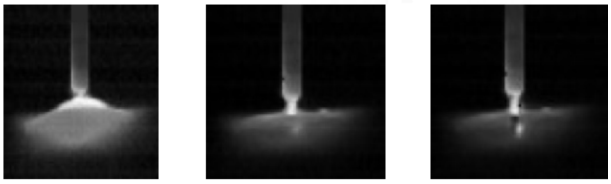
Fig. 4. GSMA brazed parts in car bodies

3. Choparc process

A new device has been invented and developed at TU Berlin in coorperation with other universities and companies. This device is for low energy process of welding and brazing known as Chop Arc process. [7]

The basic characteristic of the process is the impulse change of the curent intensity and voltage, into an impulse of special shape (Fig. 5). The impuls of the current has six separate phases determinated with characteristic points: A, B, C, D, E and O.





I_A I_B I_C

I_D I_E $I_O=0$

Fig. 5. Course of the current and voltage during ChopArc process

A. Short Circuiting, begins with current I_A. Puddle flow from the electrode tip into the melt pool with low level current I_A.
B. The Short Circuiting current increases to I_B value. Necking of the liquid metal bridge by surface tension and ohmic heating.
C. The Short Circuiting current is restricted to max. value I_C. Waiting until detachment of the metal bridge (pinching) which leads to inhibition of spater initiation.
D. Arc Ignition, the current is decreasing from I_C to I_D. At current I_D and duration t_D melting of defined melt volume and the electrode tip is effecting.
E. The current is decreasing to value I_E with duration t_E, to ensure a liquid electrode tip and melt pool.
O. The arc is cut-off, the current is switching off, $I_O=0$, for a reduction of the energy input is until next short circuiting.

4. Brazing of the zinc coated sheets with choparc process

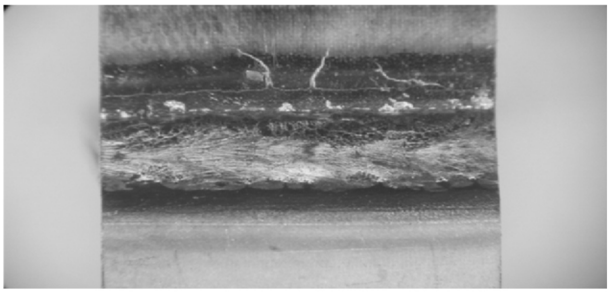
The brazing was effected on thin zinc coated sheeds with thickness of 0,75mm (Zn 54g/m^2). A filler material that was used was hard brazed in shape of wire with diameter Ø0,8mm of CuAl5Ni2 (AlBz5Ni2) alloy.

The zinc coated sheets were brazed in horizontal position at overlapping edges in length of 400mm. The brazing was effected automatically with ChopArc process in a shielding gas mix 98% Ar and 2% CO_2.

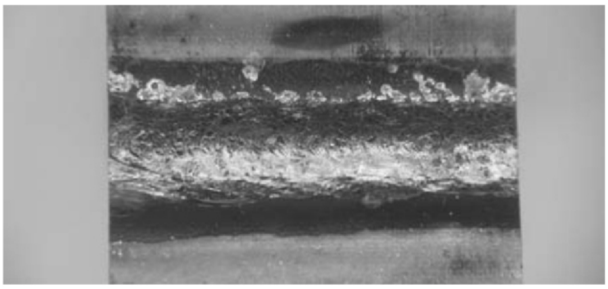
A great number of tests were brazed with constant values for: I_A, I_B, I_C, I_D, t_A, t_B, t_C, t_D, V_L, V_Z and changing values for I_E and t_E, (Table 1).

Table 1: Brazing parameters

I_A	I_B	I_C	I_D	I_E	t_A	t_B	t_C	t_D	t_E	v_L	v_z
A	A	A	A	A	ms	ms	ms	ms	ms	m/min	m/min
80	100	200	150	180-240	1.5	4.0	5.0	0.2	2.0-7.0	0.50	3.0



Sample 1, I_{E1}=180A, t_E=6ms



Sample 2, I_{E1}=240A, t_E=3ms

Fig. 6 Front surface of representative brazed samples

5. Investigation of the brazed samples

All brazed samples were visually controled, for making a selection of the brazed samples with high visual quality on its surface.

Test tubes were made from all of the chosen brazed samples, for a metalographic and share strength examinations.

The preparation and acking of the matalographic tests was effected under sugges tions from [8]. The acking was effected manualy in two phases. In the first phase the acking was effected on the brased joint, and in the second phase it was effected on the basic materials. The brazed joint was acked at room temperature during the last phase of polishing with solution Cu m5 for 10s. After the acking of the brazed joint cleaning with alcohol was performed at a room temperature and ultrasonic bath for 3min.The basic materials are beeing acked with solution Fe m1 for 5s.

All of the samples were analyzed and photographed with the optical microscope Leica DMRM with magnification from 10x to 1000x.

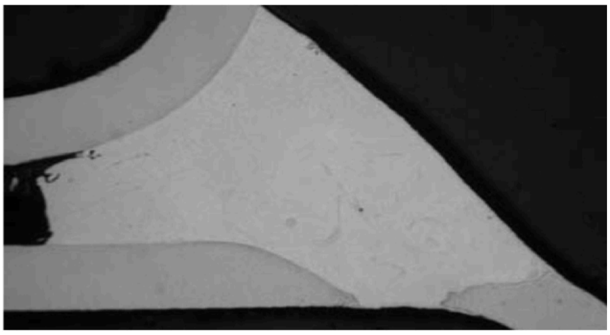
Microhardness was examined on a previusly prepared metalographic samples by Vicker's method, HV0.1, 100p/30s, strength 0,1N for period of 30s. More than 5 measurements were effected on each of the examined samples, as well as in the brazed joint and in the HAZ.

The examination by share strength was effected on at least three test tubes with width of 15mm on each of the brazed samples.

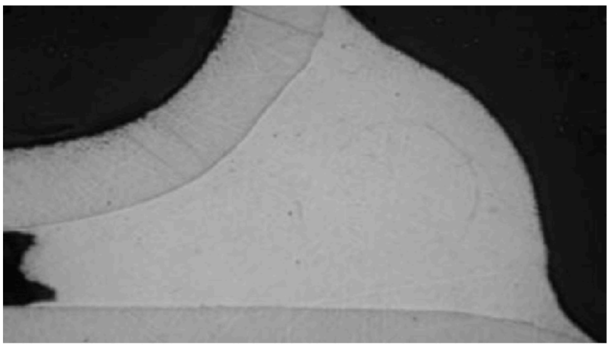
6. Results and analysis

Beside the selection of the brazed samples with high visual quality on the surface of the joint, the back side of the basic materials was also visually controled. At some of the tests a big damage of the zinc cover at back side was noticed. The reason for that was a higher imput of heat during the brazing.

Fig. 7 shows macro cross sections of the brazed Sample 1 and Sample 2, recorded unacked with magnification from 25x. One of the basic materials at Sample 1 is melted along all thickness.



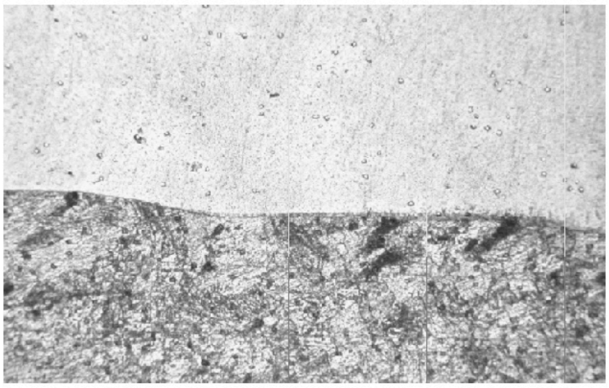
Sample 1



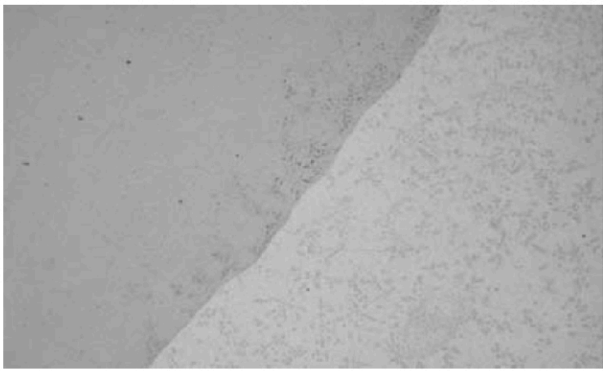
Sample 2

Fig. 7. Cross sections of representative brazed samples

Fig. 8 shows microstructure of the brazed Sample 1 and Sample 2, recorded after the acking of the basic material and the braze with magnification from 200x. A significant presence of zinc dendrits in the braze structure is noticable at Sample 1, which is not the case for Sample 2. The presence of the zinc in the braze at Sample 1 is because of the local melting of basic material.



Sample 1

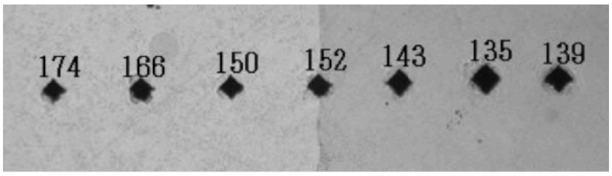


Sample 2

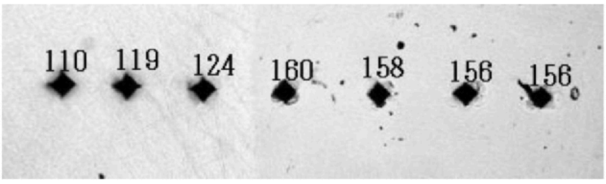
Fig. 8 Microstructure of representative brazed samples

Fig. 9 shows the results of the microhardness measurings. At Sample 1 the measured microhardness of the basic material is in the interval HV0,1=135-143 and is significantly smaller than the microhardness measured of the basic material at Sample 2, which is in interval HV0,1=156-160. The reduce of the microhardness at Sample 1 is because of the high warming up during the brazing and occurence of the recrystallisation in the basic material.

In the braze of Sample 1 the measured microhardness is in the interval HV0,1=150-174 and is much more higher from the measured microhardness in the brase of Sample 2, which is in the interval HV0,1=110-124. The increase of the microhardness in the braze of Sample 1 is because of the basic material melting and its presence in the structure of the braze.



Sample 1



Sample 2

Fig. 9 Microhardness of representative brazed samples

During the share strength examination all the test tubes were breaking fracture in the basic material, far away from the brased joint (Figure 10). The maximal strength of the tested tubes is in the interval R_m=299,6-309,3N/mm^2, which is in the interval of standard values R_m=260-330N/mm^2 for this type of materials. The strength of the brazed joint is higher than the one of the basic material, and the brazing process is not causing a change of the strength of the basic materials.

Fig. 10 Brazed samples after strength examination

7. Conclusion

The gas-shielded metal arc brazing is more and more used method of joining of the zinc coated thin steel sheets , because the result is a joint of a high quality for a small quantity of energy.

The brazed joints of thin zinc coated sheets effected by new ChopArc process are with higher quality. With an optimaly chosen parameters of the process, and at minimal and controlled input of energy we get a corrosion resistance brased joint without porosity and cracks, with strength higer than the one of the basic materials.

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РЕЗИМЕ

ЕЛЕКТРОЛАЧНО ЛЕМЕЊЕ ВО ГАСНА ЗАШТИТНА СРЕДИНА НА ПОЦИНКУВАНИ ЧЕЛИЧНИ ЛИМОВИ

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Апстракт: Во трудот е изнесен дел од резултатите добиени од истражувањето на лемењето на поцинкувани челични лимови со нискоенергетската електролачна Chop Arc постапка. Поцинкувани члични лимови со дебелина 0,75 mm (Zn 54g/m^2) залемени се со рабен спој во хоризонтална положба. Лемењето е изведено со лем CuAl5Ni2 во облик на жица со дијаметар Ø0,8 mm во заштитна гасна средина од 98% Ar и 2% CO_2.

Квалитетот на залемените споеви утврден е со металографски испитувања. Анализирана е структурата на залемениот спој и основните материјали. Вршено е и мерење на микротврдината по методот на Викерс како и испитување со затегнување на залемените споеви.

Клучни зборови: поцинкувани челични лимови; електролачно лемење во гасна заштитна средина; Chop Arc; металографска анализа; испитување со затегнување.

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IMPLEMENTATION OF ACTIVITY BASED COSTING (ABC) IN SMALL AND MEDIUM COMPANIES

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Abstract: This paper describes a procedure that allows small and medium companies to smoothly switch from a traditional costing system to an Activity Based Costing (ABC), at low risk and with minimal investment. The paper focuses on any small and medium company for which the standard implementation of ABC is too expensive and complex. The complete implementation procedure consists of eight major steps. At first, decision-makers choose among three methods, educated guess, systematic appraisal, or actual data collection, for obtaining cost information. At this stage, the decision-makers determine the level of accuracy that is needed and the amount of money to be assigned to this project. Next, the overhead expenses such as administration, rent, utilities, and transportation are complied into product cost information using newly developed matrices. Using these matrices, cost related calculations are simplified and thus the overhead costs are easily traced to the cost objects in the final step. The easy-of-use of the proposed procedure is illustrated using actual data from a medium manufacturing company.

Keywords: Activity-Based Costing, Small Business

1. Introduction

Manufacturing firms face ever-increasing competition in today's global marketplace. Companies must react quickly and manufacture high quality, low cost products to be successful in this new environment. To make proper decisions, senior managers must have accurate and up-dated costing information. Traditional costing systems based on volume-based allocation of overhead have lost relevance in a manufacturing environment that has seen a sharp increase in overhead and a subsequent decline in direct labour. These traditional costing systems tend to distort product costs and lead to poor strategic decision making [4].

One innovative costing method designed to deal with the deficiencies of traditional costing systems is Activity Based Costing (ABC). ABC, pioneered by Robin Cooper, Robert Kaplan, and H. Thomas Johnson [2,3,4,5], is a costing methodology used to trace overhead costs directly to cost objects, i.e., products, processes, services, or customers and help managers to make the right decisions regarding product mix and competitive strategies. According to Turney, ABC can radically change how managers determine the mix of their product line, price their products, identify the location for sourcing components, and assess new technology [6]. Although the literature has reported numerous implementations of ABC in large manufacturing firms, there has been limited accounting of ABC being embraced by small and medium manufacturing firms [1,7,8,9]. Upon closer examination, there appears to be several factors preventing small and medium manufacturing firms from implementing an ABC costing system including lack of data, technical resources, financial resources, and adequate computerization. Perhaps the main obstacle, lack of data, centres on the problem of collecting and processing the needed data in the correct format at a reasonable cost. Because the information needed for ABC is costly and especially small manufacturing firms are typically constrained financially, these companies need to be very selective in the type of data and analysis that they use to determine overhead costs. Moreover, small businesses operate uniquely, a condition referred to as resource poverty that requires specialized cost management approaches [5,10]. Thus, a methodology that will enable a small company to obtain accurate product cost information yet minimize financial effort is needed.

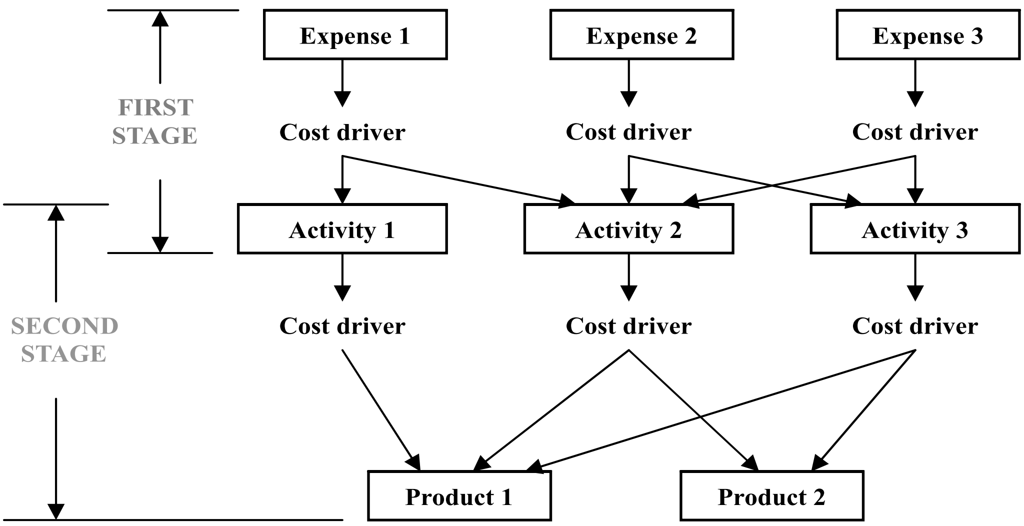


Figure 1. Relationship among expense categories, activities, and products

In this paper, an efficient and inexpensive method for implementing ABC in small and medium business environments is proposed. This procedure systematically provides the decision-maker with accurate cost information to establish corporate strategies, determine product cost, and improve the cost structure.

2. Activity Based Costing

Cooper describes two stages in the ABC model [3,4]. In the first stage, costs are assignned to cost pools within an activity centre, based on a cost driver. There is no equivalent step in a traditional costing approach. In the second stage, costs are allocated from the cost pools to a product based on the product's consumption of the activities. This stage is similar to a traditional costing approach except that the traditional approach uses solely volume related characteristics of the product without consideration for non-volume related characteristics. Some examples of cost drivers not related to volume include setup hours, number of setups, ordering hours, and number of orders. Allocating non-volume related costs' using volume-based methods distorts the product costs.

3. Methodology

In the ABC model, overhead expense categories such as administration, rent, transportation, and insurance are identified. This cost data can be obtained easily from accounting. The next step is to determine the main activities that simplify the tracing of cost information. This can be accomplished by grouping actions into activities and activities (or cost pools) into activity centres using the ABC approach. Some examples of activities for a small and medium manufacturing company are receiving a customer inquiry, customer quotes, production supervision, and shipping products. Expenses are going to be assigned to the previously defined activities via the first stage cost drivers. Following the second stage, activity cost drivers are determined to allocate overhead to individual products. Figure 1 illustrates the hierarchical relationship among expense categories, activities and products [7].

The proposed methodology assumes that the overhead cost and its categorization are available, generally from accounting. Expense categories refer to the traditional way in which a company divides manufacturing overhead. This information will assist the company in validating that the total overhead calculated at the beginning of the process matches the total obtained when summing the overhead that is assigned to each individual product using ABC.

Identifying activities or cost pools

In order to implement ABC, the complete business process should be divided into a set of activities. A flowchart of the process is a commonly used tool for identifying these main activities. Each box represents activities and arrows denote the flow of the system. Thus, in order to establish the needed activities for ABC, homogeneous processes must be grouped together [3,4,8]. In other words, product driven activities and customer driven activities must be separated in order to establish two individual homogeneous activities. Examples of activities for manufacturing companies are quote preparation, production supervision, and material handling.

Activities and first stage cost drivers

Once the main activities have been defined, a total cost of each activity can be calculated. First, the expense categories related to each activity are identified. For example, the activity cost for "quote preparation" includes costs from various expense categories such as salary, rent, utility, and office supplies. To properly trace the expenses to each activity, cost drivers, also called first stage cost drivers, have to be identified for each expense category. For instance, the expense category "rent" associated with the activity "quote preparation" may be driven by square feet, whereas, the expense category "salary" may be driven by the amount of time the employee spends on this activity.

Second Stage Cost Drivers

In the second stage, activities are traced to products using second stage cost drivers [2,9,10]. As with first stage cost drivers, data needed for second stage drivers may not be readily available to represent the proportion of cost pools that correspond to the products. For instance, mileage can be difficult to trace to individual product. In the absence of actual data there becomes a need to estimate the amount of activity cost consumed by each product.

Information Gathering Procedures

Gathering information is essential in order to achieve accuracy of final product costs. An important part of the required data is the proportions needed in each stage of an ABC costing system. Each activity consumes a portion of an expense category. Similarly, each product consumes a portion of an activity. As discussed previously, a proportion usually represents this portion. For instance, the activity "quote preparation" consumes 0.1 (10%) of administration expenses. There are many ways to obtain these proportions and the selected procedure will impact the desired accuracy. Three levels of data accuracy can be used in estimating these proportions: educated guess, systematic appraisal, and collection of real data.

Educated guess

In the case where real data can not be obtained or data collection efforts can not be financially justified, an educated guess can be made in order to obtain proportions. These guesses should be done collaboratively by management, financial organizers, and operational employees associated with the costing centre of interest. This team can provide an educated guess of the proportions of costs allocated in both stages of an ABC costing methodology. The level of accuracy obtained is based on a combination of the teams' diversity and their knowledge of the cost centre of interest.

Systematic Appraisal

A more scientific way to obtain the proportions for tracing costs is using a systematic technique such as Analytic Hierarchical Process (AHP) [4,7]. AHP is a suitable tool for pulling subjective individual opinion into more representative information. For example, assuming that the allocation of a gasoline expense is needed between three cost pools namely sales, delivery and maintenance. By questioning the departments that consume this resource and by asking them to evaluate what percentage of mileage they accumulate in a certain period of time, AHP can generate the percentage of this expense and allocate it to the appropriate cost pool.

A second area in which AHP can be used is to allocate the expense from the cost pool to each individual product. At this step it is important to determine an appropriate cost driver in order to achieve the desired level of accuracy. For example, suppose we wish to trace the sales cost pool to each product. One approach is to estimate the level of sales activity needed for each of the individual products. Let assume the following scenario: a company produces five products. Product A is a very well established product requiring minimal effort from the sales representatives when they talk to potential consumers. On the other hand, products B, C and D are in the middle of their life cycle. Finally, product E is a new product that consumes a lot of time from the sales representatives. Instead of allocating an equal amount of sales expenses to each one of the products, AHP can provide an estimation that can allow the company to more accurately trace this cost to the products. The methodology followed by AHP requires first determining factors that account for cost relationship between activities and products. In this specific illustration, locations of travel for sales and time spent with the client discussing each individual product may be some examples of these factors. Secondly, the sales representative assigns a ranking among products according to the distance needed to support them. A second raking among products is established in proportion to the time spent with the customer. Finally, the subjective rankings of sales representatives are combined by AHP and ratios for sales expenditure among the five products are obtained.

Actual data collection

The most accurate and most costly procedure for computing proportions is the collection of real data. In most cases, a data collection procedure must be developed and data collection equipment may need to be purchased. Moreover, collection of the data will need to be timely and skilled collectors may be required. The results often have to be analyzed using statistical methods. For example, job sampling can be used to estimate the time proportion dedicated to supervise the manufacturing of a particular product. In this case, the supervising engineer is asked, at random time intervals, to specify the product being currently supervised. Based on this data the needed information can be obtained.

Proposed procedure for tracing overhead expenses to cost objects

Step 1. *Get the expense categories*
The initial step is to examine the expense categories included in the income statement of the company.

Step 2. *Identify main activities*
Step 2 can be performed in parallel with Step1.

Step 3. *Relate expenses to activities by establishing an EAD matrix.*
In this step, the activities that contribute to each expense are identified and the Expense-Activity-Dependence (EAD) matrix is created. The expense categories represent the columns of the EAD matrix, whereas the activities identified in Step 2 represent the rows. If the activity *i* contributes to the expense category *j*, a checkmark is placed in the cell *i,j*.

Step 4. *Replace check-marks by proportions in the EAD matrix.*
Each cell that contains a check-mark is replaced by a proportion which is estimated using any of the procedures previously mentioned. Each column of the EAD matrix must add up to 1.

Step 5. *Obtain currency values of activities.*
To obtain the currency values of each activity the following equation is applied.

$$TCA(i) = \sum_{j=1}^{M} Expense(j) * EAD(i,j) \quad (1)$$

Where:

TCA(i) = Total cost of activity i
M = number of expense categories
Expense (j) = Currency value of expense category j
EAD (i, j) = Entry i, j of Expense-Activity Dependence matrix

Step 6. *Relate activities to products by establishing an APD matrix.*
In this step, the activities consumed by each product are identified and the Activity-Product-Dependence (APD) matrix is created. The activities represent the columns of the APD matrix, whereas the products represent the rows. If the product *i* consumes the activity *j*, a check-mark is placed on the cell *i,j*.
Step 7. *Replace check-marks by proportions in the APD matrix.*
Each cell that contains a check-mark is replaced by a proportion which is estimated using any of the procedures previously mentioned. Each column of the APD matrix must add up to 1.
Step 8. *Obtain currency values of products.*
To obtain the dollar values of each product the following equation is applied.

$$OCP(i) = \sum_{j=1}^{N} TCA(j) * APD(i,j) \quad (2)$$

Where:

OCP(i) = Overhead cost of product i
N = Number of activities
TCA (j) = Currency value of activity j
APD (i, j) = Entry i, j of Activity-Product-Dependence matrix

The procedure described can be easily implemented using common standard spreadsheet software.

4. Application Example

In this section the overhead costs of a typical medium manufacturing firm are traced using the proposed methodology. The example uses the average of actual costs tabulated from several medium-manufacturing companies to represent the costs of a 'typical' medium business enterprise. Moreover, this approach also preserves the anonymity of the companies.

Tools Inc. is a medium manufacturing company that manufactures three main products and supplies to multiple customers. Ongoing engineering work is prominent because of the use of CNC machines to manufacture products. Ten main customers are responsible for more than 80 percent of the total business. Since its foundation 20 years ago, the Tools Inc. has growth by adding three to five new employees per year. Currently, its total work force is nearly one hundred employees. Despite the growth in company size and business volume, the profitability has declined during the last few years. In the last two years, the company experienced losses for the first time in its history. Management believes that costing by intuition or by applying traditional methods is no longer appropriate. Therefore, they decided to introduce an ABC costing system to the company. Because the data required for the ABC system does not already exist and the cost to collect all of it would be prohibitive for this firm, management decided to use educated guesses, systematic appraisal, and actual data.

The initial step was to examine the expense categories included in the income statement of Average Inc. and to select cost drivers. Exhibit 2 shows this breakdown. In the second step, Tools Inc. identified its main activities and their respective second stage cost drivers as shown in Exhibit 3.

Exhibit 4 illustrates a hierarchical tree relating expense categories, activities and products. The third step determined which activities contributed to each expense category. For example, the activities contributing to the expense category "Transport" are *material receiving* and *product shipment.*

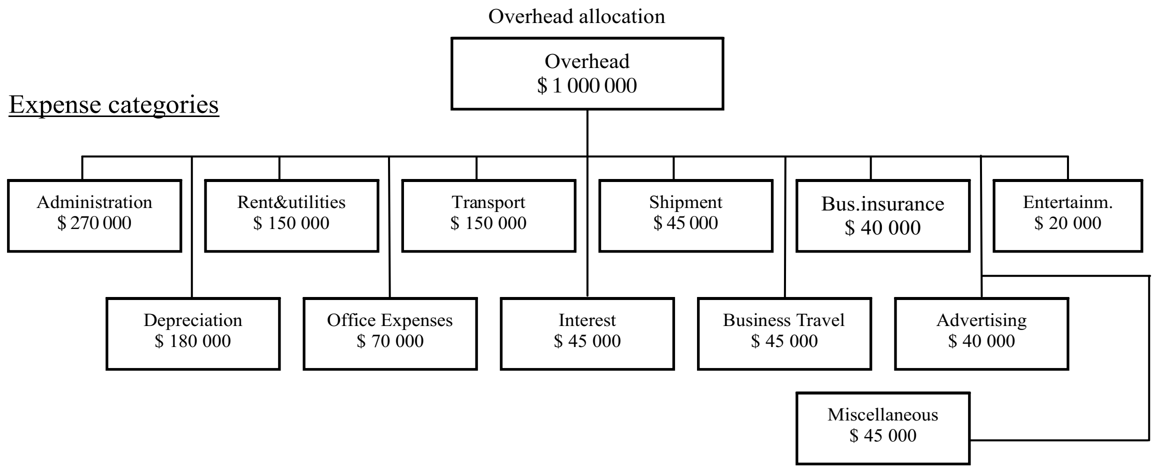
Exhibit 2. Expense categories and their respective cost drivers

Expense category	*Cost ($)*	*Cost drivers*
Administration	270,000	Time (hours)
Depreciation	180,000	Dollar use of resources ($)
Rent and utilities	150,000	Space (ft_2)
Office expenses	70,000	Level of use of office resources (%)
Transport	50,000	Distance (miles)
Interest	45,000	Cost of the activity ($)
Product shipment	45,000	Weight (Lb)
Business travel	45,000	Distance (miles)
Business insurance and legal expenses	40,000	Cost of resource used by the activity ($)
Advertising	40,000	Level of benefit (%)
Entertainment	20,000	Level of importance of customer (%)
Miscellaneous expenses	45,000	None

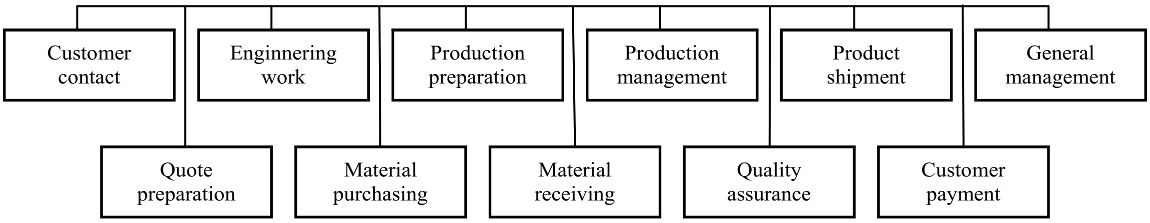
Exhibit 3. Main activities and their second stage cost drivers

Activity	*Cost driver*
Customer contact	Number of customer contacts
Quote preparation	Number of quotes
Engineering work	Engineering hour
Material purchasing	Number of purchase orders
Production preparation	Number of production runs
Material receiving and handling	Number of receptions
Production management and supervision	Product complexity
Quality assurance	Product complexity
Product shipping	Distance
Customer payment administration	Number of payments
General management and administration	Intensity of activities

Exhibit 4. Expense categories (hierarchical tree)



Activities



Products

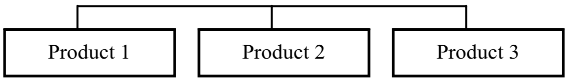


Exhibit 5. Expense-Activity-Dependence (EAD) matrix

Activities \ Expense categories	Administration	Depreciation	Rent & Utilities	Office expenses	Transport	Interest	Shipment	Business Travel	Insurance	Advertising	Entertainment	Miscellaneous
Customer contact	√		√	√				√		√	√	√
Quote preparation	√		√	√								√
Engineering work	√	√	√	√				√				√
Material purchasing	√		√	√		√						√
Production preparation	√		√	√								√
Material receiving	√		√	√	√				√			√
Production management	√		√	√								√
Quality assurance	√	√	√	√								√
Product shipment	√		√	√	√		√		√			√
Customer payment	√		√	√					√			√
General management	√		√	√		√		√	√	√	√	√

Exhibit 6. Expense-Activity-Dependence (EAD) matrix

Activities \ Expense categories	Administration	Depreciation	Rent & Utilities	Office expenses	Transport	Interest	Shipment	Business Travel	Insurance	Advertising	Entertainment	Miscellaneous
Customer contact	0.06		0.01	0.24				0.63		0.64	0.58	0.09
Quote preparation	0.10		0.05	0.14								0.09
Engineering work	0.10	0.70	0.12	0.08				0.14				0.09
Material purchasing	0.08		0.09	0.09		0.80						0.09
Production preparation	0.04		0.11	0.03								0.09
Material receiving	0.05		0.09	0.06	0.40				0.11			0.09
Production management	0.20		0.13	0.01								0.09
Quality assurance	0.10	0.30	0.20	0.02								0.09
Product shipment	0.05		0.12	0.05	0.60		1.00		0.23			0.09
Customer payment	0.04		0.01	0.08					0.46			0.09
General management	0.18		0.07	0.20		0.20		0.23	0.20	0.36	0.42	0.09

To systematically describe the contribution of activities to expense categories, the Expense Activity Dependence (EAD) matrix was used. The EAD matrix for Tools Inc. is shown in Exhibit 5. A "√" at the entry i,j denotes that the activity i generates expense in category j.

In Step four, the costs of each expense category are traced to activities. Each expense category is divided among activities according to the proportion of contribution. For instance, the expense category "Transport" is divided into two activities (material receiving and product shipment), and the ratio of contribution is 0.4 and 0.6, respectively. In this case, 0.4 and 0.6 as shown in Exhibit 6 replaces the corresponding check marks of the EAD matrix. Note that each column will sum to one, implying that the entire expense category is spread across the activities. The ratios presented in Exhibit 6 were obtained by using the three procedures described previously: actual data, systematic appraisal (AHP), and educated guesses. When data was available the ratios were determined according to the first stage cost driver. For instance, Tools Inc. tracked the miles consumed by the activities *material receiving and handling* and *product shipment* (miles is the first stage cost driver for "Transport"). The records showed that 40,000 miles and 60,000 miles were consumed by *material receiving and handling* and *product shipment*, respectively. Accordingly, the ratios for the expense category "Transport" were 0.4 and 0.6.

In Step five, every entry i,j of the EAD matrix was replaced with the resulting dollar value by multiplying the cost of the expense category j and the ratio i,j. The new matrix gives the dollar resource consumption of each activity. The total cost for each activity was obtained by adding each row. Exhibit 8 depicts the new EAD matrix for Tools Inc. with the resulting dollar resource consumption of each activity.

In Step six, activity costs were traced to each product after the total cost of each activity was determined. The procedure is similar to the one used for tracing cost in the first stage; however, second stage cost drivers allowed Tools Inc. to determine or estimate activity consumption by product. In this stage the APD matrix is used. The APD matrix for Tools Inc. is shown in Exhibit 9. In a similar fashion, a "√" at the entry i,j denotes that product i consumes activity j.

In Step seven, the check marks were replaced by the corresponding ratios.

The ratios were then placed into the APD matrix, as shown in Exhibit 10. In Step 8, the overhead costs for each product was computed. The resulting APD matrix, shown in Exhibit 11, gives the total overhead costs for each product as well as their origin.

5. Conclusion

The implementation of a new cost system involves investment in time and money. A cost system based on ABC requires organizational changes, employee acceptance, investment in software and hardware, equipment for data collection, and so on. Although, ABC has been successfully used in many large companies it does not guarantee a payback in a short period of time. By using the proposed method for implementing an ABC costing system, the risk of switching from a traditional costing system to an extensive ABC system can be reduced significantly. The proposed method is more suitable for smaller companies because it provides a smooth transition from a traditional costing system to ABC, it does not require a high investment in sophisticated data collection systems, and it does not require a serious organizational restructuring. Therefore, the proposed method can be used as an intermediate step for gradually implementing a full ABC system where the estimated data is replaced by actual data. In addition, the EAD and APD matrices assist in the comprehension of how overhead costs are generated. These matrices can also be used for recognizing improvement opportunities. As a future step a software package based on this methodology can be developed that would trace overhead cost to products accurately, at low cost, and in short time.

Exhibit 8. Expense-Activity-Dependence (EAD) matrix ($ 10,000)

Total Expenses	$27,00	$18,00	$15,00	$7,00	$5,00	$4,50	$4,50	$4,00	$4,00	$2,00	$4,50		
Activities / Expense categories	Administration	Depreciation	Rent & Utilities	Office expenses	Transport	Interest	Shipment	Business Travel	Insurance	Advertising	Entertainment	Miscellaneous	Total Cost
Customer contact	$1,62		$0,15	$1,68				$2,84		$2,32	$0,18	$0,405	$9,20
Quote preparation	$2,70		$0,75	$0,98							$0,18	$0,405	$5,02
Engineering work	$2,70	$12,60	$1,80	$0,56				$0,63			$0,18	$0,405	$18,88
Material purchasing	$2,16		$1,35	$0,63		$3,60					$0,18	$0,405	$8,33
Production preparation	$1,08		$1,65	$0,21							$0,18	$0,405	$3,53
Material receiving	$1,35		$1,35	$0,42	$2,00				$0,44		$0,18	$0,405	$6,15
Production management	$3,40		$1,95	$0,07							$0,18	$0,405	$6,01
Quality assurance	$2,70	$5,40	$3,00	$0,14							$0,18	$0,405	$11,83
Product shipment	$1,35		$1,80	$0,35	$3,00		$4,50		$0,92		$0,18	$0,405	$12,51
Customer payment	$1,08		$0,15	$0,56					$1,84		$0,18	$0,405	$4,22
General management	$4,86		$1,05	$1,40		$0,90		$1,04	$0,80	$1,68	$0,18	$0,405	$12,32

Exhibit 9. Activity-Product-Dependence (APD) matrix

Products / *Activities*	*Customer contact*	*Quote preparation*	*Engineering work*	*Material purchasing*	*Production preparation*	*Material receiving*	*Production management*	*Quality assurance*	*Product shipment*	*Customer payment*	*General management*
Product 1			√	√	√	√	√	√	√	√	√
Product 2	√	√		√	√	√	√		√	√	√
Product 3	√	√	√	√	√	√	√		√	√	√

Exhibit 10. Activity-Product-Dependence (APD) matrix

Products / *Activities*	*Customer contact*	*Quote preparation*	*Engineering work*	*Material purchasing*	*Production preparation*	*Material receiving*	*Production management*	*Quality assurance*	*Product shipment*	*Customer payment*	*General management*
Product 1	0.00	0.00	0.20	0.14	0.21	0.12	0.34	1.00	0.32	0.21	0.33
Product 2	0.53	0.60	0.10	0.34	0.27	0.41	0.27	0.00	0.26	0.38	0.33
Product 3	0.47	0.40	0.70	0.52	0.52	0.47	0.39	0.00	0.42	0.41	0.34

Exhibit 11. Activity-Product-Dependence (APD) matrix ($ 10,000)

Activity cost	$9.19	$5.02	$18.18	$8.33	$3.53	$6.15	$8.01	$11.33	$12.51	$4.22	$12.31	
Activity / Products	*Customer contact*	*Quote preparation*	*Engineering work*	*Material purchasing*	*Production preparation*	*Material receiving*	*Production management*	*Quality assurance*	*Product shipment*	*Customer payment*	*General management*	**Total Cost**
Product 1			$3,78	$1,17	$0,74	$0,74	$2,72	$11,83	$4,00	$0,89	$4,06	$29,93
Product 2	$4,87	$3,01	$1,89	$2,83	$0,95	$2,52	$2,16		$3,25	$1,60	$4,06	$27,14
Product 3	$4,32	$2,01	$13,21	$4,33	$1,83	$2,89	$3,12		$5,25	$1,73	$4,19	$42,88

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МЕТОДОТ ЗА ПРЕСМЕТКА НА ТРОШОЦИ БАЗИРАН НА АКТИВНОСТИ (ACTIVITY BASED COSTING ABC) ВО МАЛИ И СРЕДНИ ПРЕТПРИЈАТИЈА

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Апстракт: Оваа статија опишува една процедура која им овозможува на малите и средни претпријатија да преминат едноставно од традиционалниот систем на трошоци на систем на трошоци базиран на активности (Activity Based Costing, понатака во текстот ABC), со мал ризик и мала инвестиција. Статијата се фокусира на било кој тип на мала и средна фирма за која стандардната имплементација на ABC е премногу скапа и комплексна.

Комплетната процедура за имплементација се состои од осум главни чекори. Најпрвин, донесувачите на одлуки избираат помеѓу трите методи: едуцирано погодување, систематска оценка или собирање на податоци, со цел генерирање на податоци за трошоците. Во оваа фаза, одлучувачите го одредуваат потребното ниво на точност и количината на пари која треба да биде издвоена за овој проект. Потоа, фиксните/индиректните трошоци како оние за администрација, рента, сервис и транспорт се составуваат во информација за производните трошоци, користејќи ги најново развиените матрици. Со користење на овие матрици, пресметките поврзани со трошоците се поедноставуваат и индиректните трошоци лесно се лоцират на трошочните објекти во финалниот чекор. Едноставната за користење предложена процедура е илустрирана со користење на реални податоци од една средна фирма за производство.

Клучни зборови: Activity Based Costing, мал бизнис

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DETERMINING THE DECISION MAKERS' PREFERENCES IN A MCDM MODEL

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Abstract: The quantitative and comprehensible multi-criteria decision making (MCDM) approach refers to solving conflicting and multidimensional problems where it is necessary to identify, understand, address and solve conflicts and provide options for their trade-off. In the frames of a case-study, through setting a MCDM model, the MCDM concept has been utilized to address a real and existing problem defined with a set of objectives, criteria and alternatives. Since, the particular outcome of the final decision significantly depends on the preferences among criteria, this paper focuses on the results deriving from the designated survey to aggregate stakeholders' preferences among the defined set of criteria with reference to the identified and defined problem. Further steps towards proposing final solution/decision addressing the defined problem are identified.

Key words: Decision Making Theory, Multi Criteria Decision Making Modelling, Weighting Preferences, Public Transportation

1. Introduction

Accordingly to Bell and Morse [1], "*The world is a complex place and people have had to make sense of it for a long time*". The human reality is multi-dimensional and complex. Living, planning and realizing actions in this multifold reality implies coping and tackling with conflicting situations, i.e. solving derived problems and making decisions. Whatever shape or form this reality owns and whatever interferences it prepares, decisions have to be delivered on different levels and on a daily basis. "*Decision making is characterized by its involvement with information, value assessments, and optimization. Thus, whereas inventiveness seeks many possible answers and analysis seeks one actual answer, decision making seeks to choose* ***the one best answer***" [2].

A decision is easier to make when it considers only one dimension of the problem and when it involves only one decision maker. A choice and/or a solution to be delivered, in a multifold and complex en-vironment, should indicate an optimal decision under given circumstances and in precisely defined time and space limits. Such decisions are rarely unanimous and even more rarely universally supported, hence it is essential that they are transparent and reflect compromise.

Any solution to a multifold and a complex problem is only better or worse than other solutions, thus the process in which one arrives at it, has to be a good one. While the decision-maker tends to improve the final outcome of his/her decision, from a researcher's point of view, the decision-making process itself has the biggest influence on the quality of the final outcome [3].

Decision making theories adopt complex mathematical models, methods and techniques, some based on qualitative, others on quantitative approach. The qualitative approach is based on the decision maker's experience, assessment and intuition, while the quantitative tends to define the final outcome through a value or a range of values which, in turn, will define the quality of the decision. The quantitative approach is the best instrument when a problem is vague, new or complex, economic implications are extreme, existing experience (both objective and subjective) is insufficient, intuition is not an option, and it is justified to define an algorithm due to the frequent incidence of the problem.

In this paper the quantitative and comprehensible Multi-Criteria Decision Making (MCDM) theory is presented. In the frames of a case-study, the MCDM concept has been utilized to address a real and existing problem defined as “Improving the public transportation concept in the city of Skopje”. The problem has been designed and modeled through a set of objectives, criteria and alternatives, which interrelate in a specific manner.

The particular outcome of the design/decision significantly depends on the preferences among criteria. Different preferences can produce drastically different designs/decision. Thus, during the decision process, the importance of determining preferences among criteria should not be underestimated and should be dedicated a special attention. Consequently, this paper focuses on the preferences among the defined set of criteria related to the herein addressed problem.

2. Multi-Criteria Decision Making Theory

The so called Multi-Criteria Decision Making (MCDM) theory offers a comprehensible and quantitative frame to address, model and propose a solution to a complex situation where the problem related decision is based on and has to comply with several objectives. The multitude of MCDM methods and techniques can be grouped into two classes: the Multi-Attribute Decision Making and Multi-Objec-tive Decision Making methods and techniques [4,5], addressing discrete and continuous problems, cor-respondingly.

MCDM is a hard task and it sometimes offers an unwelcome objectivity. It identifies conflicts; distinguishes that which we know objectively from that which we do not; it reveals the extent to which our decisions are arbitrary and based on intuition or politics; it helps identify and understand conflicts and trade-offs; it provides an opportunity to address conflicts and, moreover, guidance to the decision maker for further discovering his/her true preference in finding the most desirable solution to the problem. MCDM assists the decision maker to understand personal values in order to create more desirable alternatives in achieving meaningful decisions. However, it has to be underlined that MCDM models do not produce perfect decisions, nor do they resolve all conflicts. They only provide useful information and insight in support of decision makers facing complex problems.

2.1. Components of the Multi Criteria Decision Making Process

Designing a particular system is a decision making process. Main components of any decision making process are the resources, the process of transformation (operators, alternatives) and the final desired state (decision in result). Main components of the MCDM process are objectives, criteria and alternatives. MCDM problems involve selection of an **alternative** from a pool of preselected alternatives described in terms of their **objectives**, accordingly to a predefined set of **criteria** [6,7]. The criteria describe standards of judgment or rules to test acceptability. When a system is driven, described, assessed and evaluated by a variety of components, one has to pick the appropriate /competitive/non-redundant set which will model the system, reflect the problem and consider criteria in the best possible way.

2.2. The MCDM Process

There exist a variety of multicriteria decision models, some better suited to some decision contexts than others. There are, however, many common elements in these various techniques, aggregated into five [8] or eight [8,9] steps.

Due to the specific local circumstances derived in the course of the here presented case-study, in this paper we propose a slightly modified approach, i.e. a ten steps process which distills these elements into comprising framework for tackling MCDM problems. This paper focuses mainly on step 3.

Step 1.Problem identification and research,
Step 2.Defining the problem relevant objectives and criteria for the MCDM model,
Step 3.Making judgments: Defining the decision maker's criteria-related preferences,
Step 4.Discussing and proposing alternatives,
Step 5.Recognizing alternatives,
Step 6.Eliminating infeasible alternatives
Step 7.Building the decision matrix for the MCDM model
Step 8.Synthesizing and ranking the alternatives
Step 9.Examining, verifying the decision
Step 10.Documenting the decision

Justification of this modification will be examined stepwise in the course of the here presented survey, as well as, in the course of other similar future case-studies.

2.3. Mathematical formulation

The mathematical formulation of the MCDM problem is given as follows. Let **x** be a K-dimensional vector of design variables (objectives) the criteria and constraints depend on and let **g(x)**0 be a vector of constraints. Then a feasible set of objectives exists. Further, let X be mapped into the criteria space S, i.e. the set of criteria $S=\{f_1, f_2,..., f_N\}$ is defined as . If the set of the alternatives is $A=\{A_1,A_2,...,A_M\}$, where every alternative is described through a set of N objectives, the MCDM problem can be described by (1) and subject to a set of constraints (2), i.e.

$$\max_{\mathbf{x}}\{f_1(\mathbf{x}), f_2(\mathbf{x}),..., f_N(\mathbf{x}) \mid \mathbf{x} \in A, \dim \mathbf{x} = K\} \quad (1)$$

$$g_r(\mathbf{x}) \leq 0, r = 1, L \quad (2)$$

The decision matrix (MxN) (M number of alternatives, N total number of the objectives/sub-objectives) (Table 1) aggregates the complete decision making related information. The element $x_{ji}=f_j(A_i)$ indicates the value of the objective X_i with respect to the alternative A_j.

Table 1. Decision Matrix

	X_1 w_1	X_2 w_2	...	X_j w_j	...	X_N w_N
A_1	$x_{11}=f_1(A_1)$	$f_2(A_1)$	...	$x_{1i}=f_j(A_1)$	...	$x_{1N}=f_N(A_1)$
...	...	...	...	...	...	...
A_i	$x_{21}=f_1(A_i)$	$f_2(A_i)$	...	$x_{ji}=f_j(A_i)$	...	$x_{iN}=f_N(A_i)$
...	...	...	...	...	...	...
A_M	$x_{M1}=f_1(A_M)$	$f_2(A_M)$	...	$x_{Mi}=f_j(A_M)$	...	$x_{MN}=f_N(A_M)$

In optimization problems where weighting is applied [10], the "best solution" can be obtained by finding:

$$\max_x U = \sum_{i=1}^{N} w_i \cdot u_i(f_i(\mathbf{x})) \quad (3)$$

where, $U(\mathbf{f})$ is the additive utility function, and u_i, w_i are the utility and weight of particular criteria.

3. Setting the Model of the Defined Case-Study: Improving the public transportation concept in the city of Skopje

The identified problem defined as "**improvement of the public transportation concept in the city of Skopje**" (IPTC), as discussed in this section, is complex and its realization depends on various variables. The expected goal is to provide good, efficient,punctual and environmentally friendly public transportation in Skopje. As a means to generate the "best" solution for the IPTC, which will comply with objectives, under certain conditions and hypotheses, a MCDM model of the problem is designed. The proposed model could serve planners and members of other concerned groups, in evaluating the viability of the alternative(s) for IPTC in Skopje, to be identified, proposed, discussed and decided upon by relevant stakeholders during the continuing course of the survey.

Tackling with this problem and delivering a final solution will be carried out through ten steps (refer to section 2.2):

3.1. Step 1: Problem Identification and Research

In accordance with the last census (2002) [11], the capital of the R. Macedonia - the City of Skopje -, considered within its current narrower limits has a population of 476,727 inhabitants. However, considered in its broader geographical limits, Skopje encompasses more than 650,000 inhabitants, i.e. more than 30% of the overall population of the country. The following reasons can be accounted for the continuous significant growing population rate of Skopje:

1.Some of the biggest industrial facilities are installed here.

2.Due to the high overall unemployment rate (officially 39% and unofficially more than 44%), particularly in the inner parts of Macedonia, people travel in and out of Skopje on a daily basis, seeking employment.

3.The biggest state university in the country is situated in Skopje. Due to the high living expenses in Skopje, students originating from cities and towns in the immediate vicinity of Skopje, as well as from some other more distant locations, choose to travel on a daily basis to attend the studies.

Due to the practical unsatisfactory efficiency of the

1.City bus network and the services provided by the City Public Transportation Utility and

2.national bus- and train networks,

the most frequently utilized transportation mean is the car, either as a personal vehicle or as a taxi. The aforementioned implies very high number of cars, mostly old, frequenting across Skopje. As a supplement to the old buses and other vehicles, they cause traffic jams, thus pollution.

R. Macedonia has two international airports; the Skopje's main airport Petrovec situated some 20 kilometers from Skopje and the smaller Ohrid airport. Although increasingly developing, Skopje still does not have a modern and reliable connection between Petrovec and the City. Potential customers of the air transport services are thus forced to either use personal transportation or the services of the taxi companies.

The biggest and only oil refinery in Macedonia is situated approx. 20 km from the center of the city, and the only efficient connection is the highway.

Due to its orography and meteorological attributes, Skopje regularly experiences winter smog episodes, induced by the heating, traffic and plant emissions [12,13].

As a conclusion, in Skopje, the public transportation and the traffic in general, represent an identified, long existing, complex and rising problem. Nevertheless, the transportation nowadays, is conditio sine qua non. Moreover, good, efficient, punctual and environmentally friendly public transportation is a necessity and should become a goal sought both by the community and the City authorities.

Under circumstances when:
1. the existing public transportation network is insufficiently developed and consists only of buses and taxis,
2. the provided services from the public (or other) utility are unsatisfactory,
3.the average age of the operational buses is 12yrs (max. 25yrs),
4. in the period 2000 2002 numerous vehicles not complying the EU standards, with average age 7 to 10 years, were allowed for import, and currently are still in use.
5. the air pollution deriving both from the use of old vehicles and the excessive use of personal vehicles used instead of the inefficient public transportation represents overall health hazard,
6. the extensive use of cars causes traffic congestions and jams,
7. the mobility of the working people in pursuit of better jobs is in constant rise and demand reliable transport network,
8. the public green surfaces are limited and potential sequestration is not recommend in order to provide space for new bus lines, etc.

alternative solutions should be opened for discussion and consideration. Such an existing, identified and defined problem seeks profound analysis, assessment and a final proposal of a possible solution for IPTC, which in result will imply improvement of the overall city's wellbeing.

Thus, the concerned pool of stakeholders need to consider, suggest and discuss
a). characteristics of the sought improved public transportation concept;
b). desired objectives deriving from the potential customers needs;
c). criteria according to which the proposed alternatives are to be judged
d). potential alternatives that should comply with the identified objectives and characteristics under a. and b. correspondingly;
e). extract the feasible alternatives
f). and decide upon the final solution which will be assessed as optimal, in accordance with the proposed set of objectives, alternatives and criteria.

Legal and well justified decisions, related to IPTC, often involve multiple objectives. The concerned pool of stakeholders involved in the judgment process is a source of numerous views, which usually do not completely agree. Often, competitive markets and interests insist on change of strategies, implying revisions of the earlier decision.

Supplementary weight, to the already defined as complex problem, is added by the fact that the overall public transportation in Skopje is under the direct authority of the municipality City of Skopje. It is responsible for issuing licenses for offering public transportation services both for the public and for the private sector. Further, the Public Transportation Utility (JSP) is founded by the City of Skopje and the City Council nominates members of the JSP's Executive Board (EB). Therefore, whenever the governing of the city undergoes political changes, JSP's EB is influenced both directly and indirectly. Consequently, any project related to IPTC, the realization of which exceeds the period of the governance of one political option, has small practical chances to be finalized.

3.2. Step 2: Defining the problem relevant objectives and criteria for the MCDM model

The selection of the set of objectives which describes the MCDM model of the defined problem was done in accordance with the following criteria:

1. the driving force/state/response framework proposed by the UN Commission on Sustainable Development (UN CSD) [14],
2. the aspects for defining relevant and non-redundant objectives and criteria discussed in [3,7,15,16], and
3. discussions and consultation with the selected pool of experts who were included in the conducted survey (refer to section 3.3).

The feedback from the conduced survey indicates that the objectives and sub-objectives are mapped into corresponding criteria as presented in Table 2[17].

Within the proposed set of objectives and criteria, the elements are grouped into four main clusters: social, economic, environmental and institutional impact; each subdivided into elements giving the hierarchy representation of the model. The number of the elements per cluster is not equal, but derived based on the afore-listed criteria.

3.3. Step3: Making judgments: Defining the Decision Makers' Objective-Related Preferences Defining Weights

As stated in section 3.1, the realization of the overall public transportation in Skopje is a responsibility and under the direct authority of the City of Skopje. The transportation services are executed by the Public Transportation Utility (JSP) of the City of Skopje which is under the direct authority of the City Council and delegates members of JSP's EB.

In addition to those buses, individual private buses are licenced to run on selected city bus lines. Obtaining a license for the private buses is, again, under the authority of the City of Skopje.

Table 2. Model hierarchy of the Defined Problem as "Improvement of the Public Transportation Concept in the City of Skopje"

Goal: Improvement of the public transportation concept in the City of Skopje	
Social impact	**(S)**
Stakeholders participation	(S1)
Improvement of public services availability	(S2)
Positive impact on City's wellbeing	(S3)
Capacity building	(S4)
Economic impact	**(Ec)**
Costs for the project – long and short term	(Ec1)
Local Economic Impact	(Ec2)
Generated Additional Income	(Ec3)
Contribution to attracting investments (foreign and national)	(Ec4)
Employment generation	(Ec5)
Transfer of Technology	(Ec6)
Environmental impact	**(E)**
Fossil energy resources preservation	(E1)
Improvement of air quality	(E2)
Land resources	(E3)
GHGs Emission Reductions	(E4)
Institutional impact	**(I)**

Having the previous in perspective, the main stakeholders from the "offering services" side can be identified among the City of Skopje, the City Council, JSP and the association of the private bus owners.

On the other side are the potential customers of the public transportation services and the wider community of the City of Skopje.

This implies that the final set of the objectives, criteria and alternatives for defining and solving the described problem is to be suggested and decided upon by the authorities in the City, however, influenced by all involved and relevant groups of stakeholders.

For this purpose, a questionnaire has been prepared. It was foreseen that during the different stages of the survey the questionnaire is distributed among a selected pool of stakeholders including experts, City's authorities, members of the JSP's EB, NGOs and representative sample of citizens. The results presented in this paper are based on the survey among a pool of stakeholders (thirty-one in total). The structure of the pool of stakeholders is presented in Table 3.

Table 3. Structure of the encompassed pool of stakeholders

Institution	Number of questioned experts
Authorities in the Municipality of City of Skopje 1. Dept. of Public Transportation, 2. Dept. of Urbanism 3. Dept. of Environmental Protection	12
EB JSP	6
Selected pool of experts	11
Bank representatives	2
Total	31

Weighted judgments are calculated based on the ongoing survey, and are presented and discussed in section 4.

4. Results and Discussion: Determining Weights

The Analytic Hierarchy Process [8,22,23] was employed to calculate judgments and preferences defi-ning corresponding weights. Five quadratic matrices A_i, i=0,1,2,3,4, with different dimension n_0=4 (four main clusters), n_1= n_3= 4, n_2=6, n_4=0, corresponding to the number of elements in each main cluster, are obtained. To retrieve the resulting weights of the criteria, the normalized principle eigenvector is computed. It corresponds to the vector of weights. The calculated aggregated weights are presented in Figure 1. As discussed in [8], it was not necessary to perform any uncertainty analysis in weighting, due to the fact that the calculated weights derive from judgments of a pool of experts and not of a representative statistical sample. Such analysis, in turn, will have to be performed when weighting preferences of the end-user's representative statis-tical sample.

As can be deduced from the obtained results, among the main criteria, the social impact (S, w_S=0.401) is considered the most significant. Among the sub-level criteria, stakeholders' participation (S1, w_{S1}=0.385), employment generation (Ec5, w_{Ec5}=0.234) and fossil energy resources preservation (E1, w_{E1}=0.389) are considered as most significant, correspondingly.

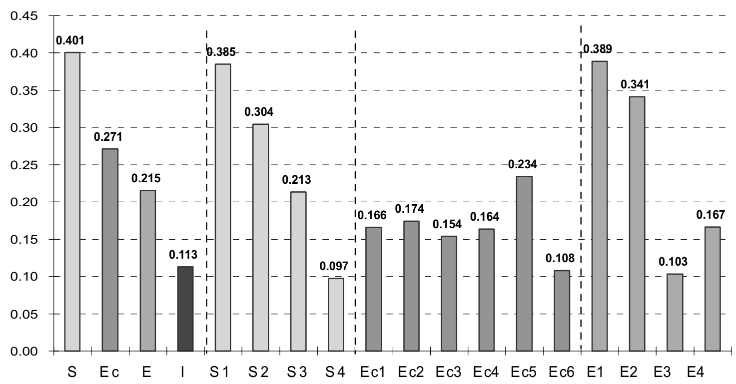

Figure 1. Calculated normalized weights for the defined IPTC MCDM model

5. Further Steps

The course of the survey is to be completed and the shape of the model for solving the problem of ICPT of the City of Skopje is to be finalized. In particular, the following steps are to be executed:

Step 4: Discussing and proposing alternatives,
Step 5: (Further) Recognizing alternatives
Step 6: Eliminating infeasible alternatives
Step 7: Building the decision matrix for the MCDM model
Step 8: Synthesizing and ranking the alternatives
Step 9: Examining and verifying the decision
Step 10: Documenting the decision.

In addition, a separate simplified survey for the end-users of the public transportation has to be designed[21].

6. Conclusion

The presented procedure for addressing the defined problem "improvement of the public transportation concept in the city of Skopje" by utilizing the concept of the MCDM, refers to solving this particular multidimensional problem encompassing four main objectives clusters, each defined by non equal number of criteria. The survey showed that the stakeholders set their preferences on the social impact (S, w_S=0.401), while among the sub-level, on the stakeholders' participation (S1, w_{S1}=0.385), employment generation (Ec5, w_{Ec5}=0.234) and fossil energy resources preservation (E1, w_{E1}=0.389), correspondingly.

The MCDM approach has not yet been used in the R. Macedonia for modeling decision making problems. Research activities as presented in this paper are expected to initiate wider utilization of the comprehensible and quantifiable frame of the MCDM theory.

7. Acknowledgements

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[17]Auth. note: During the course of the survey, the selection of the criteria, if necessary, will be further examined.

[18] Auth. note: The criteria and alternatives are to be further analyzed and discussed in the continuing course of the survey.

[19]Auth. note: Up to this moment arranging a survey among the members of the City Council is still pending.

[20]Auth. note: During the period November - December 2006 an annual meeting of the Macedonian NGOs is scheduled, and it is then foreseen to gather preferences of the NGOs representatives.

[21]Auth. note: During the conducted survey up to this moment, feed-back from citizens has been obtained. The questionnaire was installed on the web site of Eko.net portal (http://www.eko.net.mk) during a timeframe of 2 months (September October 2006). The obtained feedback was that the questionnaire was complex for a common person to understand, which was to be expected [29] since the here utilized MCDM technique is not commonly used for wide surveys, but for obtaining experts' opinion. However, based on this gained knowledge, in the future course of the planned survey, it is considered to apply an altered simplified approach, in order to obtain relevant information from the end-user, i.e. the citizens of Skopje.

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ОПРЕДЕЛУВАЊЕ НА ПРЕФЕРЕНЦИТЕ НА НОСИТЕЛИТЕ НА ОДЛУКИ ПРИ ДЕФИНИРАЊЕ НА MCDM МОДЕЛ

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Апстракт: Квантитативниот и разбирлив пристап на мулти-критеријалното носење на одлуки (multi-criteria decision making - MCDM) се однесува на решавање конфликтни и повеќедимензионални проблеми, пришто е потребно да се препознаат, разберат, кон нив да се пристапи и да се решат конфликти, но и да се обезбедат опции за нивно заменување. Во рамките на оваа студија, преку дефинирање на MCDM модел, концептот на MCDM е применет со цел пристап кон реален и постоечки проблем, дефиниран преку сет на цели, критериуми и алтернативи. Бидејќи, исходот на крајната одлука значително зависи од преференците помеѓу одбраните критериуми, во овој труд главна тежина е ставена на резултатите кои произлегоа од точно дефинирано истражување чија цел е агрегација на преференците на засегнатите страни (stakeholder-и) во однос на дефинираниот сет на критериуми кој одговара на препознаениот и дефиниран проблем. Препознаени се и следните чекори кон предлагање на крајно решение/одлука која во потполност ќе одговори на дефинираниот проблем.

Клучни зборови:Теорија на одлучување, моделирање со мултикритеријално одлучување, вреднување на преференци, јавен транспорт